The role of access to electricity in development processes

approaching energy poverty through innovation

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THE ROLE OF ACCESS TO ELECTRICITY IN DEVELOPMENT PROCESSES:

APPROACHING ENERGY POVERTY THROUGH INNOVATION

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iii Groh S, Philipp D, Edlefsen Lasch B, Kirchhoff H, Islam D, Khan MR, Chowdhury SA, Kammen DM. 2015. The Battle of Edison and Westinghouse Revisited: Contrasting AC and DC microgrids for rural electrification. *Environmental Science & Technology.* Submitted.

iv Groh S, Pachauri S, Rao N. 2015. You are what you measure! But are we measuring it right? An empirical analysis of energy access metrics. *Energy for Sustainable Development.* Submitted.

v Groh S, Philipp D, Edlefsen B, Kirchhoff H. 2015. Swarm Electrification - investigating a paradigm shift through the building of microgrids bottom-up. In: Decentralized Solutions for Developing Economies. Groh S, van der Straeten J, Edlefsen Lasch B, Gershenson D, Leal Filho W and Kammen D (Eds.). *Springer Proceedings in Energy.* XXIV. Pages 3−22.

This thesis has been submitted for assessment in partial fulfillment of the PhD degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the introductory and summary chapters of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright of published material may not be ensured. The primary data collection and basic analysis for the paper *The role of energy in development processes - The Energy Poverty Penalty: Case study of Arequipa (Peru)* formed part of my Master thesis at the University of Göttingen, Germany, under the title *Bridging the gap between micro and macro analysis - Residential and microbusiness energy demand modeling for the case of Arequipa (Peru)*. The focus, empirical analysis, conclusions and write-up for the presented chapter within this thesis, however, differ significantly from the previous thesis which can be made available upon demand.

Imprint

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Resumè på dansk

Denne afhandling adresserer rollen af elektricitet i udviklingsprocesser med det formål at give en bedre forståelse af målingen og designet af interventioner rettet mod energifattigdom, i en kontekst af udviklingslande. Afsættet for afhandlingen begyndte med hypotesen, at mennesker, som lever i energifattigdom kan være fanget i en (energi) fattigdoms straf, der indebærer negative virkninger for deres udviklingsmuligheder. Hovedresultater omfatter blandt andet, at afsides beliggenhed fra vigtige serviceinfrastrukturer cementerer disse forhold, og at høje kapitaludgifter (CAPEX) forhindrer en positiv udvikling. I visse tilfælde forværres denne strafe-effekt, specielt hvis der finds redundante infrastrukturer, som ofte er kompetitive i stedet for komplementære. Her oplever minigrids ofte en speciel form for teknologisk lock-in. Ved at bruge et multi-tier framework af energitjenesteydelser bliver kompleksiteterne af at måle adgangen til energi tydeligere, og man kan evaluere forskellige indgreb til at fremme adgangen til elektricitet. På basis af disse resultater udledes der et innovativt designkoncept, kaldt sværm-elektrificering, hvilket kan fremme elektrificeringen af landområder. Med dette som udgangspunkt, udgør fem videnskabelige artikler, skrevet og publiceret over de seneste tre år, sammenlagt kernen af denne afhandling.

Det starter med en deskriptiv undersøgelse gennemført i Peru med det formål at identificere faktorer, der bestemmer energifattigdom og undersøger de relaterede virkninger pådе samfundsmæssige udviklingsveje for et specifikt case i byen Arequipa. Undersøgelsen udvikler og differentierer et koncept af en svag og en stærk form for energifattigdomsstraf der viser, at mangel på et bestemt niveau af energiservicekvalitet forstærker niveauer af (indkomst) fattigdom. Endvidere, foreslås det at indkomst ikke er den primære faktor for energifattigdomsstraf, men snarere isolation som en fysisk distance til energiservice infrastrukturer, ofte som følge af og vedvarende mangel af økonomisk levedygtighed i at udvide sådanne infrastrukturer.

Afhandlingens anden del introducerer en case hvor en sådan energiservice-infrastruktur eller økosystem allerede er blevet etableret baseret på uafhængige solar home systems (SHS). Bangladesh repræsenterer det hurtigst voksende off-grid elektrificerings marked baseret på solenergi i verden med blandt andet mere end 3.7 millioner SHS installeret. Denne undersøgelse diskuterer kortvarig succeserne og ulemperne af denne ordning i forhold til dens evne til at levere bedre energiservicer i landdistrikterne. På baggrund af en sektors behov for en stærkere fokus på erhvervsmæssig brug af elektricitet, flytter fokus sig hen på minigrids i stedet, et område hvor betydningsfulde innovationsaktiviteter kan ses i teknologi, forretningsmodeller og politik, og som viser stor fremgang rundt om i verden og i stigende grad også i Bangladesh. På trods af det uløste spørgsmål om, hvorvidt forbedret adgang til energiservicer går forud for højere indkomst per indbygger eller omvendt, giver minigrids en infrastrukturel tilgang, som nogle hævder kan imødekomme både basal energiadgang samt erhvervsmæssig brug der vil fører til højere indkomst, hvis ellers passende designet. Dette dykker ned i designprincipper af minigrids indebærende alle tre FNs Bæredygtig Energi for Alle (SE4ALL) målene, som a) garanterer universal adgang til moderne energiservicer; b) fordobler den globale satsning for forbedring af energieffektivitet; og c) fordobler andelen af vedvarende energi i det globale energimiks. Forskningen følger og dissekerer en stor mængde litteratur og case studier implementeret omkring i verden, som beskriver minigrid designet som følger det konventionelle forsyningsnets systems spor baseret på vekselstrøms (AC) infrastruktur trods betydelig ineffektivitet der er blevet identificeret når anvendt i et grønt energi adgangs miljø. På denne baggrund leveres en yderligere undersøgelse om forskellene mellem vekselstrøm og jævnstrøm (DC) minigrids i praksis og teori. Undersøgelsen er baseret på en flerlags struktur til at måle energiadgang, der er blevet fremsat af Energy Sector Assistance Program (ESMAP) under SE4ALL initiativ. Det inkluderer et case studie på et DC-baseret nanogrid i Bangladesh. Det viser sig her, at nuværende tendenser i off-grid sektoren har positiv effekt på DC

minigrids, der ogsågør sig bedre i en komparativ analyse, men ikke desto mindre forbliver uden stor betydning på optagelse på grund af lock-in effekter. Undersøgelsen identificerer høj CAPEX i kombination med komplekse vækstmønstre af elektricitetsbehov såvel som besværligheden i at definere ejerskabsordninger som vigtige faktorer der indtil videre hindre minigrids i at have succes. Endvidere er en vigtig ulempe, specielt i tilfældet af Bangladesh, opbygningen af overflødig infrastruktur, som forværrer udfordringerne af høj CAPEX.

Specialets tredje del reflekterer kritisk på energiadgangens metrik af tidligere introducerede flerlags målingsstrukturer. Dette erbaseret på primære data fra spørgeskemaer fra landdistrikterne i Bangladesh. Afsnittet bringer det afgørende spørgsmål frem i lyset om hvad der reelt menes med universal adgang til elektricitet. Objektivitet af målingsstrukturen må ultimativt ikke søges i målingen af energiforsyningen, men rettere hvordan forsyningen muliggør vitale services (kommunikation, belysning, termisk komfort, underholdning, osv.), og hvordan disse igen kan forbedre menneskets velbefindende. Dog er målingen af energi på dette niveau af service vanskelig. Meget mere er på krævet end en simpel måling af energibærerne selv (f.eks. transformation og slutanvendelses udstyr). I fraværet af direkte måling af energitjenester, er den mest lovende tilnærmelse målingen af energi på et brugbart niveau. Af denne grund anbefales det at revidere algoritmen for at kombinere elementer fra både forsyningen og elapparaters sammensætning. Afsnittet analyserer yderligere i hvilket omfang de eksisterende forsyningsløsninger (on- eller off-grid) i Bangladesh leder til et højere niveau af forsyningskvalitet. Interessant nok er et solar home system i gennemsnit tildelt et højere niveau end en husstand i landdistrikter koblet til det nationale elnet, hvis man bruger den anvendte struktur under forskelige algoritmer. En dybdegående diskussion af de relative fordele af respektive tilgange følger.

Fjerde og sidste del har til formål at indkorporere læringen fra analysen af tidligere afsnit ved at komme op med en normativ undersøgelse af et innovationsbaseret koncept af en jævnstrømsinfrastruktur baseret på deling og bygget op fra bunden. Især har det til formål at besvare de rejste spørgsmål af fysisk isolation, muligheder for at generere indkomst, høje kapitaludgifter samt overflødige infrastrukturer. Afsnittet er baseret på hypotesen at minigrids bygget op fra bunden undgår reguleringsmæssige afhængigheder og kan leder til mere modstandsdygtige og i sidste ende bæredygtige infrastruktursystemer. I den undersøgte anordning, møntet som sværmelektrificering, deler hver husstand/mikrovirksomhed i et sværm-intelligent netværk information med dens naboer for at opnå effekten afen netværksforbindelse individuelle, enkeltstående husstande og deres energisystemer er lænket sammen således de danner et minigrid, hvorved der opnås effekten af et elnet, hvilket er baseret på udveksling af elektrisk strøm. Dermed har det designede system evnen til at integrere infrastruktur; det kan vokse dynamisk uden eller med kun et begrænset antal af enkelte centraliserede administrerende enheder, og gøre det muligt at have stabile delsystemer eller systemer med muligheden for at fungere uafhængigt af hinanden. Når det efterfølgende kommer til beslutningen om, hvorvidt man skal udvide regionale eller nationale elnet til fjerntliggende områder eller ej, forbedrer sværm-elektrificeringsmodellen sandsynligheden for økonomisk levedygtighed, da sværm-netværket repræsenterer et aktivt elektrisk distributionsnetværk af sammenkoblede husstande og mikrovirksomheder, der også kan udvide infrastruktur mod det etablerede forsyningsnettet. Konceptet anvendes i tilfældet af Bangladesh baseret på dens infrastruktur af mere end 3.7 millioner SHS installeret i landdistrikter til dato.

Imens understreges vigtigheden af at sikre universal adgang til moderne energi servicer, specielt på baggrund af den beviste eksistens af en energifattigdomsfælde, bidrager afhandlingen til analysen af og betingelser for konceptet energifattigdom, men ikke gennem synet af et binært system (on-grid vs. off-grid) men nærmere gennem et kontinuum af forbedring med henblik på elektriske tjenesteydelser. Forfatteren yderligere designer og vurderer en innovativ løsning, der har evnen til at skabe en transitionsproces fra et enkeltstående system til en netværkseffekt, hvilken vil give et bedre resultat for hvert individ i et szstem under dynamisk udvikling. Omend muligheden for et sværm-elektrificeringstilgang mangler at blive bevist i praksis, åbner afhandlingen op for nye diskussioner om hvorvidt innovationer kan fremme decentralisering og demokratisere elektriske servicer i diskursen om den Globale Syd. Den danner således en del af det stigende mængde af tværfaglig forskning omkring energifattigdomog bidrager til det lovende syn at de rette aktører med deeffektive værktøjer kan spille en væsentlig rolle i at forbedre adgangen til energitjenester for alle.

Deutsche Zusammenfassung

Die Dissertation adressiert die Rolle von Elektrizität in Entwicklungsprozessen im Globalen Süden mit der Absicht, ein besseres Verständnis für die Bewertung und Gestaltung von Maßnahmen, die auf die Beseitigung von Energiearmut abzielen, zu erarbeiten. Die Arbeit fußt auf der Hypothese, dass Menschen, die unter Energiearmut leiden, unfreiwillig in eine Energiearmutsfalle geraten, welche wiederum negative Auswirkungen auf das Entwicklungspotenzial der Bevölkerung mit sich bringt. Wesentliche Erkenntnisse der Arbeit sind unter anderem, dass die Abgelegenheit von Schlüsselserviceinfrastrukturen diesen Status hervorruft, während hohe Kapitalkosten eine Veränderung zum Positiven verhindern. In spezifischen Fällen wird dieser Umstand durch ein Phänomen von redundanten Infrastrukturen, die oftmals statt sich zu ergänzen miteinander konkurrieren, noch verstärkt. Dies trifft insbesondere im Kontext von kleinen Inselnetzen zu, die zudem häufig unter einer speziellen Form eines technischen Lock-in-Effektes leiden. Bei der Anwendung eines multiplen Rangfolgesystem zeigt sich außerdem die Komplexität, die bei einer Messung von Energiearmut einhergeht. Darüber hinaus werden verschiedene Energiedienstleistungen bewertet. Aufbauend auf diesen Ergebnissen, wird eine neue Gestaltungsinnovation, namens Schwarmelektrifizierung, als eine mögliche Zukunftsperspektive für die ländliche Elektrifizierung entwickelt. Fünf wissenschaftliche Aufsätze erforscht, geschrieben und publiziert -oder im Prozess der Publikation- aus den letzten drei Jahren formen den Kern dieser Dissertation.

Sie beginnt mit einer deskriptiven Studie auf Basis einer Fallstudie, die in Arequipa, Peru, durchgeführt wurde, mit dem Ziel die Faktoren zu identifizieren, die einen Zustand von Energiearmut bestimmen und die damit korrelierenden Auswirkungen auf den gesellschaftlichen Entwicklungspfad zu untersuchen. Die Studie entwickelt ein theoretisches Konzept einer Energiearmutsbestrafung und zeigt dabei auf, inwieweit ein Mangel an einem gewissen Grad an Energiedienstleistungsqualität den Zustand von (Einkommens-) Armut weiter verstärken kann. Darüber hinaus suggeriert die Arbeit, dass Einkommen (Erschwinglichkeit) nicht der primär determinierende Faktor für eine Energiearmutsfalle darstellt, sondern eher Abgelegenheit, hier verstanden als physische Distanz, von Energiedienstleistungsinfrastrukturen. Der Aufbau dieser Infrastrukturen wird oft als ökonomisch nicht rentabel bewertet.

Der zweite Teil der Arbeit beschäftigt sich mit einem Fall, bei dem eine solche Energiedienstleistungsinfrastruktur oder aber ein ganzes Ökosystem rundum autonome solare Heimsysteme herum bereits etabliert wurde. Mit unter anderem mehr als 3,7 Millionen installierten solaren Heimsystemen repräsentiert das Land Bangladesch den am schnellsten wachsenden solar gestützten netzfernen Markt der Welt. Die Analyse diskutiert hier in Kürze die Errungenschaften und Rückschläge dieses Programms anhand dessen Beschaffenheit verbesserte Elektrizitätsdienstleistungen in ländlichen Gegenden bereitzustellen. Vor dem Hintergrund eines industrieweiten Aufrufs sich zunehmend auf den produktiven Nutzen bereitgestellter Elektrizität zu konzentrieren, schwenkt die Arbeit ihren Fokus im weiteren Verlauf auf kleine Inselnetze, ein Gebiet, auf dem signifikante Innovationen im Bereich von Technologie, Geschäftsmodelle und der politischen Linie beobachtet werden können und die weltweit, inklusive in Bangladesch, im Aufschwung scheinen. Trotz der ungelösten Frage, was zuerst kommt für die Menschen, ein verbesserter Energiezugang oder ein erhöhtes pro Kopf Einkommen, versprechen die Befürworter von kleinen Inselnetzen eine Elektrizitätsinfrastruktur bereitzustellen, die, sofern adäquat gestaltet, beides umfassen kann, einen fundamentalen Zugang zu Energie und produktiven Nutzen, der schließlich zu höheren Einkommen führen soll. Die Abhandlung vertieft sich hier in die Gestaltungsmöglichkeiten von kleinen Inselnetzen anhand der drei Ziele der Nachhaltige Energie für Alle Initiative (SE4ALL) der Vereinten Nationen: a) die Sicherung eines universellen Zugangs zu modernen Energiedienstleistungen; b) die Verdopplung der globalen

Wachstumsrate von Energieeffizienz und c) die Verdopplung des Anteils an erneuerbaren Energien im globalen Energiemix. Die Gestaltung und Analyse folgt hierbei der sowohl in der Literatur als auch in der praktischen Implementierung gegenwärtigen Tendenz den konventionellen Weg der Energieversorger zu wählen, nämlich eines auf Wechselstrom basierten Systems, trotz dessen beträchtlichen Ineffizienzen, die für den Fall einer grünen Wiese Umgebung in Bezug auf den Zugang zu Energie recherchiert werden. Um dem entgegenzuwirken, beschäftigt sich eine weitere Studie dieses zweiten Teils mit einer Gegenüberstellung von Wechsel- und Gleichstrom basierten kleinen Inselnetzen. Es liegt ihr ein Rahmensystem zu Grunde, das den Zugang zu Energieversorgung anhand von multiplen Rängen untersucht, das von dem Energy Sector Assistance Program (ESMAP) unter dem Mantel der SE4ALL Initiative eingeführt wurde. Das Kapitel beinhaltet außerdem eine Fallstudie zu einem kleinen Gleichstrom basierten Inselnetz in Bangladesch. Es wird aufgezeigt, dass die derzeitigen Neuerungen im netzfernen Bereich kleine Gleichstromnetze begünstigen, die dadurch auch in einer komparativen Analyse relativ besser abschneiden. Dennoch bleibt deren Aufnahme gering, was so genannten Lock-in-Effekten zugeschrieben wird. Ein zentrales Ergebnis dieses zweiten Teils ist es, dass hohe Kapitalkosten in Kombination mit komplexen Energienachfragewachstumsmustern sowie die Frage des Eigentumsanspruchs kritische Faktoren sind, die bis dato den Erfolg von kleinen Inselnetzen verhindern. Eine weitere Einflussgröße, die zum Misserfolg führen kann, spezifisch für den Fall in Bangladesch, ist der Aufbau von redundanten Doppelinfrastrukturen, die die Problematik der zu hohen Kapitalkosten weiter verstärken.

Der dritte Teil der Arbeit besteht aus einer kritischen Reflexion der zuvor eingeführten Energiezugangsmetrik basierend auf multiplen Rängen mit Hilfe von Primärdaten, die mittels Fragebögen im ländlichen Bangladesch ermittelt wurden. Das Kapitel beleuchtet die entscheidende Frage, was wir eigentlich damit meinen, wenn wir von universellem Zugang zu Elektrizität sprechen. Ziel eines jeden Messsystems zur Energieversorgung muss im Endeffekt sein, nicht zu messen, wie viel Energie/ Elektrizität angeboten wird, sondern stattdessen inwieweit dieses Stromangebot wesentliche Dienstleistungen (Kommunikation, Licht, Wärme, Unterhaltung, etc.) bereitstellen kann und wie diese wiederum das menschliche Wohlbefinden verbessern. Das Messen von Energie als Dienstleistung ist jedoch sehr schwierig. Dies liegt darin begründet, dass es weitaus mehr als einer bloßen Messung von Energieträgern bedarf (zum Beispiel: Energieumwandlung und Endverbraucher). Die vielversprechendste Alternative zur direkten Messung ist die von nutzbarer Energie. Deswegen wird empfohlen, die Algorithmen des von den Vereinten Nationen empfohlenen Ansatzes derartig zu ändern, dass ein zusammengesetzter Algorithmus entsteht, der die Elemente des Stromangebotsmessansatzes und des Stromverbrauchermessansatzes miteinander verbindet. Das Kapitel geht weiterhin darauf ein, wie die in Bangladesch derzeit angewandten Lösungen, die einen Energiezugang ermöglichen sollen, in dem multiplen Rangfolgesystem bewertet werden. Interessanterweise schneiden die Haushalte, die über ein solares Heimsystem verfügen, im Schnitt besser ab als diejenigen, die Zugang zum nationalen Stromnetz haben. Eine detaillierte Diskussion zu den jeweiligen Vorteilen verschiedener Elektrizitätszugangslösungen wird hierzu vorgenommen.

Der vierte und letzte Teil der Abhandlung unternimmt den Versuch, die Erkenntnisse der vorausgehenden Kapitel miteinander zu verbinden und anhand einer präskriptiven Studie ein innovatives Konzept einer Gleichstrom basierten Strominfrastruktur mit Wechselnutzung im Aufwärtsverfahren zu entwickeln. Vornehmlich versucht das Konzept die Themen Abgelegenheit, Chance der Einkommensgenerierung, hohe Kapitalkosten und redundante Doppelinfrastrukturen zu adressieren. Das Kapitel basiert auf der Hypothese, dass bei kleinen Inselnetzen, die im Aufwärtsverfahren aufgebaut werden, Pfadabhängigkeiten vermieden werden können und diese zu stärker resilierenden und letztlich nachhaltigeren Energieinfrastrukturen führen. Im untersuchten System, das als Schwarmelektrifizierung umschrieben wird, teilt jeder Haushalt bzw. jedes Kleinunternehmen in einem Netzwerk von Schwarmintelligenz Informationen mit seinen Nachbarn aus, um einen verstärkten Netzwerkeffekt zu erzielen. Dies bedeutet im konkreten Fallbeispiel, dass individuelle solare Heimsysteme elektrischen Strom untereinander dadurch teilen, dass sie miteinander verknüpft werden, um ein Kleinstromnetz zu bilden und einen Netzwerkeffekt zu generieren. Folgerichtig hat das entworfene System die Fähigkeit, bestehende Infrastrukturen zu integrieren, dynamisch zu wachsen ohne oder zumindest nur mit einer stark reduzierten Anzahl von Zentralsteuerelementen und zudem als ein stabiles Teilsystem eines Ganzen zu fungieren. Im gesetzten Fall von Entscheidungen bezüglich regionaler oder nationaler Netzintegration verbessert sich die ökonomische Bewertung der Ausgangslage für den Einzelnen, da sie im Komglomerat einen miteinander verbundenes und aktives Stromnetzwerk darstellen, das die Fähigkeit besitzt, zum Netz des Stromversorgers hin zu schwärmen. Das Konzept wird für die Fallstudie Bangladesch und seiner bestehenden Infrastruktur von bis dato mehr als 3,7 Millionen solaren Heimsystemen in ländlichen Räumen angewandt.

Während die Bedeutung des Ziels eines universellen Zugangs zu modernen Energiedienstleistungen zu sichern, insbesondere vor dem Hintergrund der bewiesenen Existenz einer Energiearmutsfalle, in der Arbeit unterstrichen wird, steuert die Abhandlung im Wesentlichen dem Versuch bei, das Konzept Energiearmut weitergehend zu analysieren, allerdings nicht auf Basis der Betrachtung eines binären Systems (ans Netz angebunden oder nicht), sondern eher auf Basis eines kontinuierlichen Verbesserungspotenzials von Elektrizitätsdienstleistungen. Der Autor gestaltet und bewertet des Weiteren ein innovatives Konzept, das einen Übergangprozess von einem eigenständigen System zu einem Netzwerkeffekt aufzeigt mit dem Fokus darauf, dass in einem dynamisch wachsenden System jeder einzelne Haushalt anhand des multiplen Rangsystems besser abschneidet. Wenngleich der Schwarmelektrifizierungsansatz die Praxisprobe noch bestehen muss, so eröffnet doch die Abhandlung neue Diskussionsebenen in Bezug auf die Frage, inwieweit Innovationen im Umfeld des Globalen Südens zu dezentralen und demokratischen Elektrizitätsdienstleistungen führen können. Sie wird somit zu einem Teil der wachsenden Zahl von interdisziplinären Arbeiten zum Thema Energiearmut und steuert damit der vielversprechenden Aussicht bei, dass die richtigen Akteure mit effektiven Methoden, eine entscheidende Rolle für eine Verbesserung des Zugangs zu Energiedienstleistungen für alle einnehmen können.

English abstract

The thesis addresses the role of electricity in development processes with the aim to provide a better understanding of the measurement and design of interventions targeting energy poverty in a developing country context. The impetus for the dissertation begins with the hypothesis that people living in energy poverty can be trapped in an (energy) poverty penalty that implies adverse effects for their development opportunities. Major findings include, among others, that remoteness from key service infrastructures constitutes this status and high capital expenditure (CAPEX) hinders positive change. In specific cases, a phenomenon of redundant double infrastructures, which are often of competitive instead of complementary nature, exacerbate the situation, especially in the context of minigrids that frequently suffer from a special form of technological lock-in. Applying a multi-tier framework also shows the complexities involved when measuring energy access and evaluates different energy service interventions. Based on these findings, a novel design innovation, coined as swarm electrification, is derived as one possible way forward for rural electrification. Five scientific papers, researched, written and published -or awaiting publication- over the past three years, form the core of this dissertation.

It opens with a descriptive study conducted in Peru aiming to identify factors that determine the baseline status of energy poverty and correlated implications on societal development paths for a specific case in Arequipa. The study develops the concept of an energy poverty penalty showing that the deprivation of a certain level of energy service quality reinforces the status of (income) poverty. Furthermore, it suggests that income (affordability) is not the primary factor for an energy poverty penalty but rather remoteness as the physical distance to energy service infrastructures often resulting from and persisting due to a lack of economic viability in extending such infrastructure.

The second part of the thesis introduces a case where such an energy service infrastructure or eco-system has already been established based on stand-alone solar home systems (SHS). The country of Bangladesh represents the fastest growing off-grid solar electrification market in the world with more than 3.7 million SHS installed, among other energy access technologies. The study briefly discusses the successes and drawbacks of this scheme with regard to its proficiency in delivering improved energy services in rural areas. Against the background of a sector-wide call for a stronger focus on productive uses of the delivered energy, the study shifts the focus on minigrids, an area where significant innovation can be observed in technologies, business models, and policy and that experiences a major up-take around the globe and increasingly also in Bangladesh. Despite the unresolved question on whether improved access to energy services precedes higher per capita income or vice versa, minigrids provide an infrastructural approach, which some claim can accommodate both basic energy access and productive use of the delivered energy that lead to higher income if suitably designed. The paper here dives into design principles of minigrids bearing in mind all three United Nations (UN) Sustainable Energy for All Initiatives goals (SE4ALL), which are a) ensure universal access to modern energy services; b) double the global rate of improvement in energy efficiency; and c) double the share of renewable energy in the global energy mix. The research follows and dissects a large body of literature and case studies on implementation around the globe, which describe minigrid designs that follow the conventional utility grid systems path based on alternating current (AC) infrastructure despite considerable inefficiencies that have been identified when applied in a greenfield energy access environment. Against this backdrop, a further study contrasts alternating and direct current (DC) minigrids in practice and theory. The study is based on the multi-tier framework to measuring energy access, which has been put forward by the Energy Sector Assistance Program (ESMAP) under the umbrella of the SE4ALL Initiative. It includes a case study on a DC-based minigrid in Bangladesh. It is shown that current trends in the off-grid sector positively affect DC minigrids, which also

perform better in comparative analysis than AC powered ones but nonetheless remain low on up-take due to lock-in effects. The study identifies high CAPEX in combination with complex growth patterns of electricity demand as well as difficulty in defining ownership schemes as key factors that thus far hindering the success of minigrids. Additionally, an important drawback, specifically in the case of Bangladesh, is the build-up of redundant infrastructures exacerbating the challenges of high CAPEX.

The dissertations third part critically reflects on the energy access metrics of the previously introduced multi-tier measurement framework, applying it to questionnaire-based primary data from rural Bangladesh. The chapter illuminates the crucial question of what is actually considered to be universal electricity access. The objective of any measurement framework must ultimately lie not in measuring the supply of energy/ electricity, but rather how this supply enables certain vital services (communication, illumination, thermal comfort, entertainment, etc.), and how these in turn improve human well-being. This, however, can get difficult as much more is required than a simple measurement of the energy carriers themselves (e.g. transformation and end-use equipment). In the absence of a direct measurement of energy services, the most promising approximation is measuring energy at the useful level. For this reason, it is recommended to revise the frameworks underlying algorithms in order to devise a compound algorithm that combines elements from both the supply and the appliance framework analysis. The chapter further analyzes the extent to which the existing energy access solutions (on- and off-grid) in Bangladesh lead to higher tiers. Interestingly, on average, a solar home system is assigned to a higher tier than a rural household connected to the national grid when using the candidate framework under different algorithms. An in-depth discussion of the relative merits of the respective approaches is presented.

The fourth and last part aims to incorporate the learning from the analysis of the previous chapters by developing a prescriptive study founded on the innovation concept of a sharing-based DC electricity infrastructure built from the bottom-up. In particular, it aims to address the issues of physical remoteness, income generation opportunities, high capital expenditure as well as redundant infrastructures. The chapter is based on the hypothesis that minigrids built from the bottom-up avoid path dependencies and lead to more resilient and ultimately more sustainable infra-systems. In the investigated swarm electrification scheme, each household/ microbusiness in a swarm intelligence network shares information with its neighbors to achieve a compounding network effect - individual stand-alone household energy systems are linked together to form a minigrid, thereby achieving a networked grid effect based on the sharing of electrical power. Consequently, the designed system has the ability to integrate legacy infrastructure in order to dynamically grow without or with only a limited number of single centralized managing units, and to allow for stable sub-systems or systems with the ability to function independently. Subsequently, when it comes to the decision of whether or not to extend regional or national grid connections for remote areas, the swarm electrification model improves the likelihood of economic viability, as the target community represents an active electrical distribution network of interconnected households and microbusinesses that can also extend infrastructure towards the utility grid. The concept is applied to the case of Bangladesh based on its legacy infrastructure of 3.7 million+ SHS installed in rural areas to date.

While underlining the importance of ensuring universal access to modern energy services, especially given the proven existence of an energy poverty penalty, the dissertation contributes to the effort of analyzing the concept and conditions of energy poverty, not through the lens of a binary system (on-grid vs. off-grid) but rather through a continuum of improvement in terms of electricity services. The author further designs and assesses an innovative scheme that has the capacity to shape an evolutionary process from a stand-alone system to a grid-like network focusing on delivering higher tier level of service for each individual in a dynamically evolving system. Whereas the feasibility of the swarm electrification approach remains to be proven in practice, the dissertation opens up new discussions on the extent to which innovations can facilitate decentralized and democratized electricity services in a Global South setting. It thus forms part of the growing body of interdisciplinary knowledge surrounding energy access and contributes to the promising view that the right actors, using effective tools, can play a major role in improving energy service access for all.

About the author

Sebastian holds a Bachelor degree in Economics from University of Mannheim (Germany) and Universidad Carlos III de Madrid (Spain) as well as a Masters degree in International Economics from the University of Göttingen (Germany), University of Pune (India) and Universidad José Matías Delgado (El Salvador). Having joined as a Ph.D. fellow at Aalborg University, he continues to form a part of the Postgraduate Program Microenergy System at the Technische Universität Berlin. Sebastian further received an executive training on strategic leadership for microfinance from Harvard Business School and is a Stanford Ignite Fellow of 2013 from Stanford Graduate School of Business.

After having turned his back on the trading floor in Frankfurt (Germany), he has been working extensively across the world at the intersection of energy service provision and microfinance foremost as a consultant at MicroEnergy International. Sebastian is living and working in Bangladesh as the director of two newly founded companies, ME SOLshare Ltd. and ME Fosera Bangladesh Ltd..

Abbreviations

2SLS	Two Stage Least Square
AC	Alternating Current
BDT	Bangladeshi Taka
BoP	Base of the Pyramid
CAPEX	Capital Expenditure
CAYG	Cash-in-As-You-Go
CFL	Compact Fluorescent Lamp
DC	Direct Current
DRE	Distributed Renewable Energy
EC	European Commission
EDI	Energy Development Index
EPP	Energy Poverty Penalty
ESMAP	Energy Sector Management Assistant Program
EU	European Union
GoB	Government of Bangladesh
HDI	Human Development Index
ICT	Information and Communication Technology
IDCOL	Infrastructure Development Company Limited
IEA	International Energy Agency
IFC	International Finance Corporation
IV	Instrument Variable
LCOE	Levelized Cost of Electricity

LED	Light-emitting Diode
MCA	Multiple Correspondence Analysis
MDG	Millennium Development Goal
MES	Microenergy System
MFI	Microfinance Institution
NPV	Net Present Value
O&M	Operation & Management
OLS	Ordinary Least Square
OMV	Omitted Variable Bias
OPEX	Operational Expenditure
OSIPTEL	Organismo Supervisor de Inversin Privada en Telecomunicaciones
PAYG	Pay-As-You-Go
PBS	Palli Bidyut Samity
PCA	Principal Component Analysis
PO	Partner Organization
PQLI	Physical Quality of Life Index
PV	Photovoltaic
R&D	Research and Development
RE	Renewable Energy
REB	Rural Electrification Board
RERED	Rural Electrification and Renewable Energy Development
RESET	Ramsey Regression Equation Specification Error Test
RSF	Rural Service Foundation
S/.	Peruvian Soles
SAM	Swarm Area Manager
SD	Standard Deviation
SDG	Sustainable Development Goal
SE4ALL	Sustainable Energy for All
SELV	Safe Extra Low Voltage

SHS	Solar Home System
TEA	Total Energy Standard
Tk.	Taka
UN	United Nations
USA	United States of America
USD	United States Dollar
WB	World Bank
WEO	World Energy Outlook
Wh	Watt hour
Wp	Watt peak

Chapter 1

Introduction

"1.3 billion people lacking access to electricity today and we had the same figure 20 years ago, right? - This energy access sector must really suck!"

- Energy access practitioner at the MES 2015 conference in Bangalore during a plenary discussion in April 2015

"We won't solve climate change unless we also seriously tackle energy poverty, and we haven't really solved energy poverty if we ravage our planet in the process. [...] The World Bank already has success stories to build on: in Bangladesh [...]."

- Senator John Kerry in a speech at the World Bank, 2009

Introduction

1.1 Background

In September 2000, the largest gathering in history of world leaders took place in New York. Back then I was 14 years old, and my Latin American high school teacher encouraged us to take part in a project to clean car windshields at a neighboring fuel station. The earned money was to be donated to a street kid program she supported. Unfortunately, we had a little accident at the fuel station causing damage, which by far outweighed the funds we managed to raise. For me, this represented an early taste of a phenomenon I should re-visit many times thereafter, while working in developing countries: Good intentions are simply not enough and may come at a high cost [Novogratz, 2009]. Nonetheless, in this very same year that the Millennium Declaration was adopted, also my interest for the developing world was triggered for the first time.

Five years later, in September 2005 the Millennium Development Goals (MDGs) were declared. To the great disappointment of a whole sector, energy did not find its way into the formulation of the world's eight time-bound and quantified targets for addressing extreme poverty in its many dimensions. For years to come researchers would study intensively to show the linkage between energy access and development opportunities. The conviction grew that none [of the MDGs] can be achieved without the availability of adequate and affordable energy [Sovacool et al., 2012, pg. 272]

Six years later, in 2006, the Grameen Bank jointly with Prof. Muhammad Yunus received the Nobel Peace Prize *"for their efforts to create economic and social development from below"* [Media, 2006] which can be very well seen as the media break-through of microcredit. Owing to this achievement, further members of the Grameen conglomerate received more media attention. Grameen Telecom, for instance, received publicity through its village phone program where rural women are empowered to own a cell-phone and turn it into a profit-making venture [Telecom, 2015]. A key shortcoming was the lack of a source to power these phones, among other appliances, which gave birth to Grameen Shakti in 1996, a renewable energy social enterprise. By 2006, Grameen Shakti had managed to sell about 75,000 solar home systems to people, that were not connected to the national grid, based on monetary installments mirroring their kerosene expenditure [Shakti, 2015]. The company showcased two important points here; first, it proved wrong a fundamental belief that was common in the rest of the world at that time, namely that solar photovoltaic (PV) is too expensive as an electricity source. Second, and more importantly, it gave a figurative example of the interconnectedness of energy access and income generation. As a part of the Grameen family, Grameen Shakti shared the Grameen Bank's objective of alleviating poverty for the extreme poor through microcredit and energy inclusion.

Today, fifteen years later, I present my doctoral thesis that deals with the role electricity plays in development processes, and investigates in detail the question of what determines energy poverty, what keeps people in this state and how to overcome it. At the same time, the post-2015 Development Agenda is being discussed, again in September, and again in New York, only that this time 'energy for all' made it onto the list of the proposed Sustainable

Development Goals (SDGs) [UNSDKP, 2015]. In the meantime, the solar home system sector (SHS) in Bangladesh has accomplished close to four million system installations to date [IDCOL, 2015] while a company, named d.light, the market leader in the solar lantern sector has managed to sell over 10 million systems in 62 countries [d.light, 2015].[1]

Twenty-five to thirty years from now, almost all the growth in energy demand will be attributed to the developing world [Wolfram et al., 2012]. The world's poor and nearly poor will play a key role in driving medium-run growth in energy consumption. Energy consumption, again, is not only a key factor for economic growth but at the same time the main driver of greenhouse-gas emissions [Jakob et al., 2014]. This led to a strong call to avoid carbon lock-ins and instead to engage into a less-carbon intensive development path in the Global South. Whereas there is no doubt that such a path is globally desirable, it remains a matter of public discourse whether a de-coupling of economic growth and energy-related emissions is feasible given that it imposes considerable costs and is a matter of global justice. Heated by gridlocked climate change negotiations, the discourse further led to discussions on potential trade-offs between efforts towards electricity for all and emission reduction targets [Moss et al., 2014]. In response, Pachauri [2014] analyzes the case of India, a country where more than 400 million have an electricity deficit, the largest share of people in the world [Pachauri, 2014]. She concludes that irrespective whether this part of the population will be connected to electricity generated by solar or coal, meeting the energy needs of the poor is unlikely to contribute significantly to global greenhouse gas emissions. In a nutshell, aspirations to provide universal electricity access should be given clear priority, independent from its generation source. In some cases, hybrid models in decentralized settings may be the best choice as they have the potential to create co-benefits [Jakob et al., 2014; Bhattacharyya, 2015; Chowdhury et al., 2015]; [Chapter 3]. A recent report by Practical Action even argues that in order to successfully achieve universal energy access, it must be paired more robustly with the climate agenda because only then will viable decentralized options gain the necessary spotlight to become visible for policy makers and the finance community, which in turn is needed for a major scale-up [Leopold, 2014].

As a corollary, despite the apparent success in the case of Bangladesh, increasing voices doubting the accomplishments of the energy access sector[2] are heard. Between 1990 and 2010 1.7 billion people gained access to national grid electricity, in the same time frame, global population expanded by 1.6 billion people [IEA and WB, 2014]. Furthermore, there seems to be a consensus that the predominant binary criterion for measuring energy poverty/ access is not sufficient to provide a necessary reflection of the multi-faceted and multi-tier nature of energy access [Bazilian et al., 2010]. Therefore the questions remain: Do we really understand the underlying concept of energy poverty? Or even more fundamental, is there a generally agreed upon underlying concept? And further to that, provided energy for all constitutes a SDG, do we have the right tools in hand to accomplish this goal and are we equipped to monitor this process? Only what gets measured is what gets done. So far excluded from the MDGs but about to enter the SDGs, it is now more than ever the right time for academia to

[1] Solar lanterns, often also referred to as pico-lighting systems, typically range in a 0.1 to 10Wp generation range and retail prices vary between USD 10 to USD 100 [Alstone et al., 2015]. One could draw the range for SHS from 10 to 135Wp based on retail costs between USD 75 to USD 750, depending on the exact configuration.

[2] The energy access sector is understood here as a distinct group of actors that engage into the goal of addressing energy poverty. This group of actors involves the public, academic and private sector.

deliver not only a way to measure energy poverty but also to investigate the most effective ways to overcome it. As such, this thesis forms part of the promising view to give the right players effective tools so that they can play a major role in combating energy poverty. The remainder of this introductory chapter is therefore strongly orientated toward the interplay between electricity (access) and human development centering on an understanding of a continuum of electricity services.

1.2 Electricity and human development

To put it in the words of UN Secretary-General Ban Ki-moon:

> *"Energy is the golden thread that connects economic growth, increased social equity, and an environment that allows the world to thrive. Access to energy is a necessary precondition to achieving many development goals that extend far beyond the energy sector eradicating poverty, increasing food production, providing clean water, improving public health, enhancing education, creating economic opportunity, and empowering women. The transition to sustainable energy systems also presents one of the greatest investment opportunities of the 21st century. In short, development is not possible without energy, and sustainable development is not possible without sustainable energy." [Ki-moon, 2011, pg. 5]*

A necessary (pre-) condition[3] for a specific event or state X is a condition that must be satisfied in order for X to be able to be obtained. Necessary and sufficient conditions are often used in relation to questions of causality. It goes without saying that energy access is not a sufficient condition for the development goals outlined above. In their pioneering work Goldemberg et al. [1985] have set the cornerstone for the analysis of the link between energy and human development [Goldemberg et al., 1985]. The authors rightfully mark out that *"the consumption of energy is not an end in itself. Increased energy use is valuable only insofar as it improves the quality of life by providing energy services (. . .)"* [Goldemberg et al., 1985, pg. 191]. The authors contend that since increased welfare generated through rapid economic growth have not shown the expected trickle-down effects, rapid economic growth as a measure to eradicate poverty has equally failed to hold as a sufficient condition. They further argue for a direct allocation of resources in order to meet basic human needs, including energy access, leading directly to poverty reduction. At the same time, there is no empirical evidence suggesting that targeting basic needs leads to a slow-down in economic growth but possibly the contrary due to increases in worker productivity. This corollary has led to an on-going discussion to this day on how much energy one needs in order to meet ones basic energy requirements. The focus here has been to come up with certain thresholds of energy use per capita.

[3]The suffix 'pre' in combination with necessary seems to be redundant here.

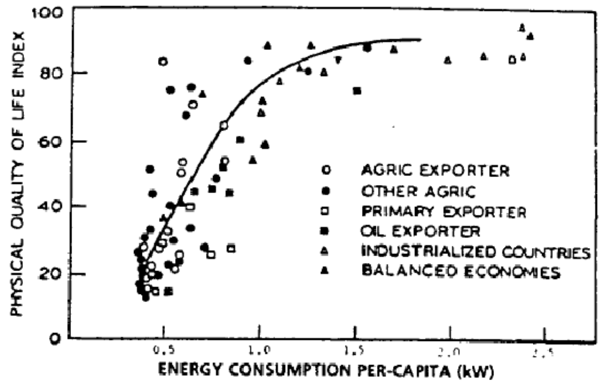

Figure 1.1: The physical quality of life index vs. total per capita energy use Source: Goldemberg 1985

Supported by figure 1.1 above, Goldemberg et al. [1985] were the first to come up with a number. Plotting the Physical Quality of Life Index (PQLI) that focuses on three very basic measures of infant mortality rate, life expectancy, and literacy, against energy consumption per capita measured in kW, they observe that at a value of 90 in the PQLI, which is typical for industrial countries), about 1-1.2 kW energy per capita is consumed where further increases only correspond to a marginal increase in the PQLI. Even though these results are characterized by considerable scatter, almost three decades later, Steinberger and Roberts [2010] and Steckel et al. [2013] come up with similar values [Steinberger and Roberts, 2012; Steckel et al., 2013]. Given the criticism for GDP as being a poor indicator for human development [Fleurbaey, 2009; Kubiszewski et al., 2013], they equally choose an alternative gauge while still including a measure of economic wealth: the Human Development Index (HDI). Even though neither is without conceptual drawbacks, the HDI is *"a summary measure of average achievement in key dimensions of human development: a long and healthy life, being knowledgeable and have a decent standard of living"* [UNDP, 2011, pg. 1] and finds its roots in Sen's capability approach [Sen, 1999].

Using actual energy consumption, Steckel et al. [2013] derive two threshold lines, specifically 42 GJ/a (or 1.3kW) and 100GJ/a (or 3.2kW) that correspond to a high and very high development status, respectively, as defined by the United Nations Human Development Program [UNDP, 2011]. In this respect, they are able to replicate the results of Steinberger and Roberts [2010], who use primary energy as the explanatory variable. What is striking in figure 1.2 is the observation that for some countries whose development is depicted in time steps of five years over the period from 1980 to 2005 (e.g. India, Costa Rica and China) to a certain extent seem to climb up in the HDI while keeping their per capita energy use fairly steady. The same pattern emerges when time is frozen in 2005 for all countries in the world, namely that at this point of time up to a certain level over a heterogeneous set of countries some are more developed based on HDI values than others but still use roughly the same amount of energy. This can probably be explained to a large extent by the dominant share of household energy use, as at these stages of development there is usually very little demand from industry which emerges significantly at a later stage and may change this relationship. This hypothesis can be supported by the findings from Steinberger and Roberts [2010] showing that energy use over

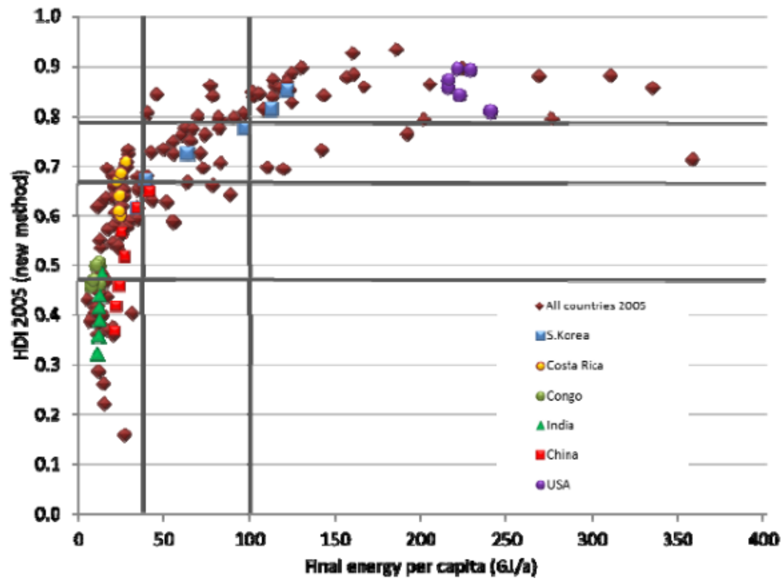

Figure 1.2: Correlation of final energy use and HDI Source: Steckel et al. 2013

time is more strongly coupled with economic activity whereas human development factors like life expectancy and literacy are increasingly decoupled. Life expectancy and literature are strongly increased with access to modern forms of energy but less so with ever increasing energy use of the same. It may lead to the conclusion that the largest impact on the goal of improving people's quality of life may be gained from giving those people basic energy access that are deprived of it, as this is where the positive correlation seems strongest. This is in line with the chorus of the energy and development debate that is dominated by statements suggesting that energy is a precondition for development in terms of the MDGs [Ki-moon, 2011]. At least two arguments speak in favor of this hypothesis. First, opportunity costs of low efficiency energy services seem to be especially high at lower levels of development [Toman and Jemelkova, 2003], who bears this cost in the end depends on the respective subsidy structure of a country. Second, an energy poverty penalty (EPP) may have the potential to prohibit or at least delay societal development paths [Groh, 2014]; [Chapter 2]. A monetary impact on income per capita, however, finds less empirical proof in these macro analyses.
Coming back to figure1.2, this relationship changes as we approach HDI levels higher than 0.74 where significantly higher energy use levels are needed. The question on what comes first, energy or development, has inspired a plethora of studies. While it seems obvious that on the macro level strong development paths, proxied by GDP per capita growth over time, have been accompanied by strong increases in energy consumption, literature on this nexus remains inconclusive at best in terms of both existence and direction of causality [Ozturk, 2010; Payne, 2010; Menegaki, 2014]. This is concerning as a thorough understanding of energy dependency or neutrality is of high relevance when it comes to policy formulation. Knowing whether energy use precedes higher per capita income or vice versa, gives us the opportunity to direct our limited resources at the cause and not the consequence. If those studies, clustered for different income levels, were to be summarized, empirical results on the macro level rather find evidence for a uni-directional causality running from economic development to energy use [Ozturk, 2010; Apergis and Tang, 2013]. In her meta-analysis on the energy-development

nexus, Menegaki [2014] distinguishes past papers in different generations of econometric modeling. Here, each generation comes up with more sophisticated models aiming to account for heterogeneity endogenously. The degree of inconclusive results, however, remains unchanged. A consequence to this dilemma is to look closer at actual numbers and allow for the assumption that the causality may in fact change multiple times along a development path which, in turn, explains in part the inconclusiveness of the majority of the macro-level causality papers. The first step in an energy-based development path is undoubtedly to provide basic energy access in order to reach certain thresholds. Steinberger and Roberts [2010] further show that these threshold values can vary over time and are expected to decrease in the future (e.g. due to future efficiency improvements). This declining trend also seems to outpace population growth which implies an absolute decrease in the total energy required for a high global level of human development [Steinberger and Roberts, 2012, pg. 431]. In other words, given saturation effects at high levels of energy consumption, and rebound effects (Jevon's paradox) in combination with increased efficiency of the delivery of essential energy services, in the case of more equally distributed resources, current energy supply levels are sufficient to satisfy global human needs at high levels of human development.
From the analysis conducted so far, the case stands rather in favor of a causality running from energy access to human development at least at low levels of development. Alstone et al. [2015] take a closer look at this relationship by running a correlation analysis between access to electricity and HDI as well as to selected Millennium Development indices for the time frame from 2000-2010 [Alstone et al., 2015].

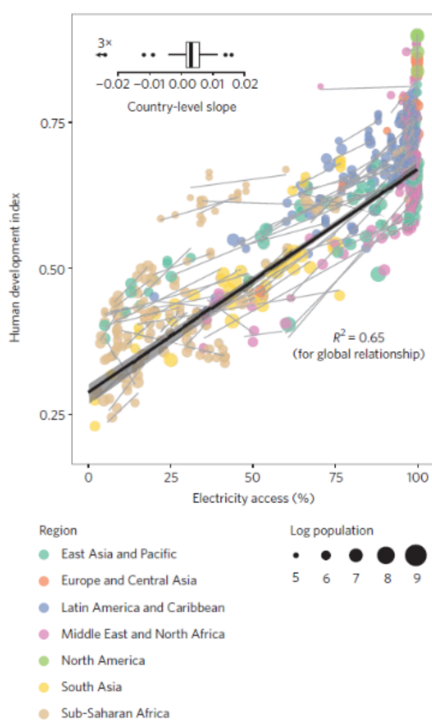

Figure 1.3: The relationship between access to electricity and the HDI for 2000-2010 Source: Alstone et al. 2015

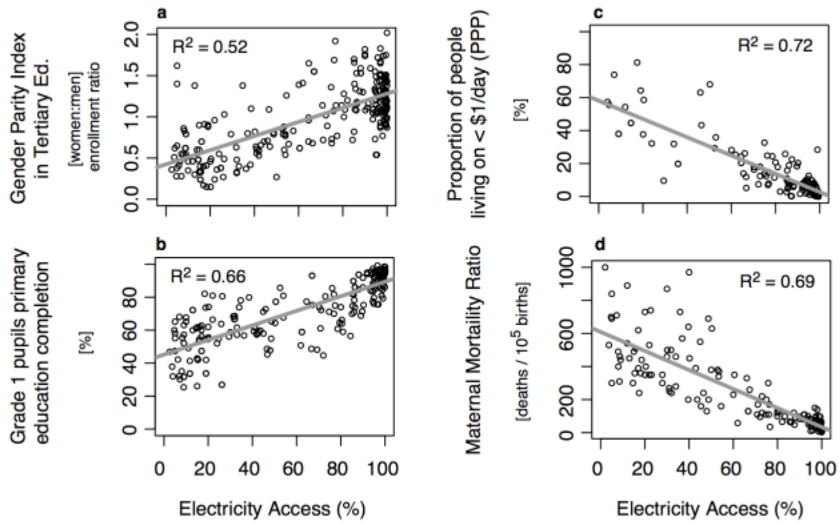

Figure 1.4: The relationship between access to electricity and selected MDGs for 2000-2010 Source: Alstone et al. 2015

Figure 1.3 and 1.4 suggest that more than half of the variation in human development can be explained by access to electricity or some correlate of the same. The correlation in figure 1.3 may very well be improved by further distinguishing the regional differences in this area. In contrast to the consumption based graphs, here a linear relationship can be detected where access is shown to be *"a first-order linear predictor of the HDI along with an important set of selected MDGs over its full range"*[Alstone et al., 2015, pg. 306]. There is still no proof for a statistically causal relationship, nonetheless these results give support to earlier made statements that the causality is in fact changing over time. Electricity access may here be understood as the very low range of the GJ/a consumption levels of figure 1.2 and analyzing it is like putting a magnifying glass on the seemingly puzzling relationship in this spectrum. A possible explanation may very well be that once a significant portion of the population gains access to basic electricity, the broad scale Gj/a metric is not significantly affected but at the same time the path is set for significant increases in HDI. For yet higher levels of HDI, in turn, significant investments in infrastructure are necessary, as explained by Steckel et al. [2013], leading to a considerable increase in energy usage per capita. In addition, certain technological, social and institutional factors are at play, which cannot be easily captured by macro level data [Alstone et al., 2015]. Among them are energy efficiency appliances, alternative technology options, concurrent and complementary use of the same, different types and degrees of remoteness, village politics, etc. that are addressed in detail in the up-coming chapters. Their exclusion in (inter-)national statistics at times even causes misleading energy policy implications [Groh et al., 2015]; Chapter 5]. A large part of this thesis is therefore focused on a bottom-up assessment of energy poverty/ electricity access.[4]

[4]Even though electricity only forms one part of energy poverty, at times it is been used interchangeably in the context of this thesis.

1.3 Energy poverty

The criterion of necessity for measuring energy poverty/ access is still the ratio of people lacking access to an electric grid connection, and being dependent on traditional biomass for cooking to the total population, respectively [IEA, 2012]. At times, these measures are supplemented by estimates of the number of people who suffer from an intermittent electricity supply, although intermittency lacks a clear definition [AGECC, 2010]. Notably, indoor air pollution, an impact from cooking traditional solid fuels and using kerosene based lighting, is among the most important global causes for morbidity and mortality [WHO and IHME, 2014]. Despite equal importance in moving people out of energy poverty [Barnes et al., 2013], this thesis only touches upon the issue of dependency on traditional biomass and its implications for development in chapter 2, whereas the remaining chapters are solely dedicated to the use of electricity.

Latest data indicates that about 1.166 billion people, 17% of the world population, suffer from an electricity access deficit. Most of this population resides in Sub-Saharan Africa and South Asia (87%), and in rural areas (85%) [IEA and WB, 2014]. Notwithstanding its crucial role in fostering human development, present 2030 projections estimate that under business as usual *"600-850 million people in rural South and Pacific Asia and sub-Saharan Africa could remain without electricity"* [Pachauri et al., 2013, pg. 4]. Lighting services are often met with insufficient, high cost alternatives [Mills, 2005; Groh, 2014]; [Chapter 2]. Moreover, the affected population is exposed to increased health risk and safety issues [Lam et al., 2012]. The SE4ALL initiative, based on data from the IEA, estimates that to reach its goal of universal electricity access 30% of the rural population will require access to the national grid whereas 70% of the rural population may gain access through decentralized solutions, approximately 65% via minigrids[5] and 35% via individual solar systems in their homes [IEA and WB, 2014]. Yet another field of intervention, that is worth considering *"not merely as a derivative of [...] electricity, but an instrumental energy service in its own right"* is mechanical power [Sovacool, 2012, pg. 717] as here the link to income-generating activities is supposedly most direct.

Income and energy poverty are two intertwined concepts [Barnes et al., 2013]. The macro-level pattern of the phenomenon of development without considerable energy use at very low energy consumption levels as described by Steckel et al. [2013] is mirrored at the micro level in figure 1.5. The x-axis is based on income deciles as per capita measures, the y-axis on end use energy measured in kilograms of oil equivalent per capita per month (kgOE/person/month). Energy consumption seems to undergo a variable elasticity pattern. Although energy consumption is income inelastic at low income groups, it turns income elastic for households with higher incomes. Barnes et al. [2013] argue that the income inelasticity stems from the fact that those levels represent the basic needs which have to be met in order to sustain life and therefore determine a critical energy poverty line directly related to income poverty. Biomass consumption is included in their data.

[5]Note: The dissertation uses the terms minigrid, microgrid and nanogrid. Whereas the term mini- and microgrid are often used interchangeably, in the Bangladeshi context nanogrids refer to much smaller grids in reaching only up to a couple of kW of capacity. However, there is no consensus on a formal definition for the same.

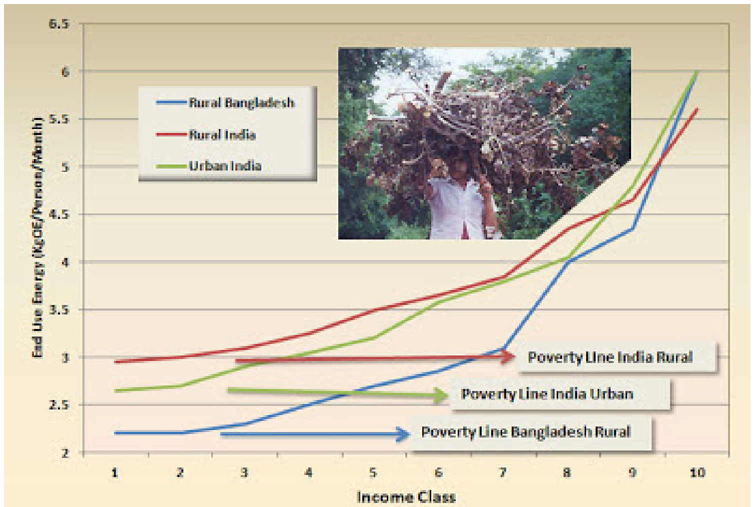

Figure 1.5: Energy End Use Energy Consumption by Income Class, Bangladesh and India Source: Barnes et al. 2013

This relationship is striking, and somewhat supports macro level claims. On the other hand, however, it does not yet tell us whether simply lifting all households into income class three will allow them to deal with energy poverty themselves, or whether we need to improve energy access first which will subsequently cause income to increase. An initial conclusion is that it turns out to be highly contextual. For instance, applying Barnes' poverty lines results in 59% energy poverty in rural India coupled with only 23% income poverty. This implies that many rural Indian households could afford improved energy services, but are stuck with using energy in more traditional ways. So here, energy poverty does not track income poverty. In short, the causality question remains inconclusive at the macro and the micro level. What we could clearly see, however, is a changing relationship between energy consumption and human/ economic development at different stages of development. Chapter 2 on the energy poverty penalty will look further into this question.

"There is a growing consensus that measurements of energy access should be able to reflect a continuum of improvement" [IEA and WB, 2014, pg. 6] in contrast to relying on a (binary) uni-dimensional measure as outlined above. It must not be reduced *"to merely two services or two sets of technology"* [Sovacool, 2012, pg. 718]. The value of energy access is determined by a range of factors, which in part are very difficult to measure such as *"intra-household power dynamics, electric grid management, geographic diversity, political relationships and concurrent access to complementary technology"* [Alstone et al., 2015, pg. 306]. There is no general rule on what might cause a status of energy poverty as it is highly contextual. Whereas, there is often the talk of geographical remoteness as a key factor in rural areas, surprisingly little research has been done for household living literally below a low-voltage grid line but yet without a connection to the grid [Lee et al., 2014]. They find that despite significant investments being done in grid infrastructure in Kenya, in areas considered as ideal setting (high population density and extensive grid coverage) electrification rates remain very low. A key reason behind this occurrence may be the lack of end user financing for the physical connection which often goes hand in hand with the struggle in obtaining permission for the

same as the households may or may not be settled in official housing areas. This shows that it should be made a key requirement for any measurement approach of energy poverty to be able to identify the main cause of the present energy poverty status by means of a gap analysis, so that effective interventions can be designed to overcome them at minimum cost.

Considering energy poverty as an *"absence of sufficient choice"* with reference to the capability approach [Sen, 1999], one needs to pin down individual welfare components and assess how they interact as multidimensional causes of development and deprivation. Under the framework of the Global Tracking Framework, an attempt for this was put forward by the World Bank's Energy Sector Management Assistance Program (ESMAP): the multi-tier framework that has been heralded as a new *"milestone"* in energy measurement [Bensch, 2013, pg. 4]. The candidate framework assesses energy access along several attributes (e.g. durability, affordability, etc.) measured either by binary indicators or along a graded scale. A combination of these individual attribute's performances determine the assignment to a specific tier, which in turn reflects the level of electricity access of the object of investigation. It thus aims to measure a *"continuum of improvement, based on the performance of the energy [service] supply"* [ESMAP, 2014]. Further, it aims to enable policy makers to identify critical shortcomings along the different attributes. Still, *"defining energy poverty metrics and respective targets is a complex task"* [Bazilian et al., 2010, pg. 15]. Often, a trade-off between *"methodological sophistication and theoretical accuracy on the one hand, and applicability and transparency on the other"* is unavoidable [Bazilian et al., 2010, pg. 17]. When it comes to a consensus building process for a universal measurement framework among the SE4ALL member countries, this may lead to conflict as the performance evaluation of country specific energy interventions can differ significantly based on the measuring algorithm used. The multi-tier framework is discussed in greater detail in chapter 6 and in part in chapter 4.

1.4 Decentralized energy systems and innovation

Most of the poor live in emerging markets [WB, 2013]. In these countries mobile connectivity has outpaced the electricity grid [Nique and Smertnik, 2015]. In the last decade grid intensification clearly lacked behind the rapid expansion of mobile network resulting in 643 million people covered by mobile networks but without access to electricity which represents more than half of the estimated off-grid population. Research shows that many of these people are forced to spend significant time and money for mobile phone recharging [Alstone et al., 2015]. The mobile market has demonstrated what a growth path at the base of the pyramid can look like. In the time frame from 2000 to 2012, mobile phone subscriptions increased from fewer than one billion to around six billion [WB, 2012]. 72% of the people in low-to-middle income countries are using a mobile phone, a 20-fold increase since 2000. What seemed to be crucial is that the consumers valued the mobile phone as a large benefit at a comparatively low cost, meaning there was a strong drive by the users themselves, whereas in the energy space mostly utilities and the government are expected to take the driving seat [Welsch et al., 2013]. As a result, during the same time period, the energy sector in turn, has not shown this degree of innovative activity [Groh et al., 2015]. Having been dominated by monopolies with partial or full ownership of regional grids, incentives for innovative actions have been far from ideal often leading to underinvestment in new technology and business model development [Margolis and Kammen, 1999]. This structure is severely hindering an innovation-based strategy for energy access. Energy policy literature does not make an exception here, and has shown little interest in energy poverty measures, despite its importance in affecting billions of people every day [Sovacool, 2012]. In fact, until 2008, among the articles published in the top energy journals only 8% addressed issues related to energy poverty and development [D'Agostino et al., 2011].

In the past few years, energy access and innovation have received more of a spotlight, not least triggered by two consecutive special reports on the topic by the International Energy Agency in 2010 and 2011, the introduction of the Energy Development Index (EDI) by the same in 2012, as well as the announcement of a decade for sustainable energy for all at the end of 2012 by the United Nations General Assembly [IEA, 2010, 2011, 2012; UN, 2012]. Increasingly, the focus shifted away from a strictly centralized framework toward a more decentralized perspective which finds its resemblance in the energy access scenarios that predict 70% of the electrification is goint to be performed by decentralized systems [OECD and IEA, 2011; IEA and WB, 2014]. The solar off-grid market as well has experienced rapid growth in the past five years where key markets include countries like Bangladesh, India, Ethiopia, Kenya, Tanzania, and Peru [Jacobson, 2015]. While declining solar PV prices support this trend, gains in energy end-use efficiency seem to have played an even more important role to reduce overall system prices. Furthermore, the sector has made tremendous progress by piggybacking on innovations within the information and telecommunication technology (ICT) sector, in particular its mobile payment applications. Access to consumer capital for solar home systems is triggered by cutting down the prohibitive initial cost into installments that can be paid through the mobile phone, referred to as Pay-As-You-Go (PAYG) [Alstone et al., 2015]. This innovative approach that gained momentum mostly in East Africa is now also spreading to other parts of the world (e.g. Pakistan, Philippines, among others). This is just one example of how technology innovation can leverage base of the pyramid business models and is discussed further within Chapter 5 and 6. More recently, innovative schemes have been put forward in India and Bangladesh of how to optimally make use of mechanical energy applications, especially in the agricultural sector such as different mills or solar water pumping units. These still come at a considerable cost and typically face seasonal demand with limited usage times over the day. The suggestion therefore, is to integrate them into nanogrids as an anchor load but also augment demand in terms of usage times [Khan and Brown, 2015; Mehra, 2015].

The idea of feasible decentralized energy systems to meet basic needs of a larger part of the populations is by no means a new concept. It finds its first prominent introduction in the early 70s though E.F. Schumacher's description on appropriate technology in his influential work *"Small is Beautiful"* [Schumacher, 2011]. The criteria for methods and equipment to be developed by scientists and technologists have remained unchanged since then and equally lead the present thesis:

- *"cheap enough so that they are accessible to virtually everyone;*
- *suitable for small-scale application; and*
- *compatible with man's need for creativity"* [Schumacher, 2011, pg. 21].

Within this work, reference is made to these systems as microenergy systems (MES). A MES is defined as a *"decentralized energy system based on small energy appliances, which provide*

households, public institutions, [and] small businesses with energy and enables energy demand to be met by locally-based sources" [v.d. Straeten et al., 2014, pg. 139].
Multiple dimensions of remoteness represent acute energy isolation barriers, in terms of geographical distance, financial means and political power play that often prevent an improved energy service supply [Alstone et al., 2015; Groh and Koepke, 2014]. This applies especially in the case of centralized service provision whereas MES do not require the same support network. The direct link between generation and consumption in a MES enables a more scattered application. Moreover, a super-efficiency trend has led to continuous improvement in end-use efficiency for LED lighting and 12V DC appliances, such as TVs, projectors for village cinemas, fans, refrigerators, etc. [Jacobson, 2015]. These developments allow MES *"to compete with legacy equipment, on a basis of cost for energy service, for basic household needs"* [Alstone et al., 2015, pg. 307]. This leads to a situation where it is no longer clear ex ante whether the national grid or different forms of MES perform better in a multi-tier measurement framework as discussed in chapter 5. End-users find themselves in a situation where they are equipped with multiple types of electricity infrastructures to fulfill their energy needs as depicted in figure 1.6 below.

Figure 1.6: Impression on multiple lay-overs of electricity infrastructures in Bangladesh Source: MicroEnergy International, 2013

The three co-existing electricity infrastructures on the photograph are stand-alone solar home systems, a hybrid minigrid and the national grid. Additionally, if we were to look inside the houses, we would find different switches and lights for each related piece of electricity infrastructure. One can only imagine the daunting nature of the evaluation of the value of electricity access at the point where centralized and the decentralized approaches meet each other. Despite changing energy use patterns along the development path, minigrids are still often understood as a one-time intervention which have yet to live up to the expectations associated with them [Bhattacharyya, 2015; Chowdhury et al., 2015]; [chapter 3]. So far, from the private sector perspective, self-sustainable minigrid models with a business rationale are still very hard to find [Manetsgruber and Wagemann, 2014]. Figure 1.7 below suggests a somewhat evolutionary process from a stand-alone solar home system, via step-by-step interconnection in various forms of minigrids, to a national grid interconnection where the degree of complexity is growing with each step. The approach can be understood as the most decentralized of a MES where the grid is built from the bottom-up [Groh and Koepke, 2014]; [chapter 6]. It further requires certain smartness in its technological configuration in order to allow it to dynamically move toward a bigger network facilitating a higher level of service provision.

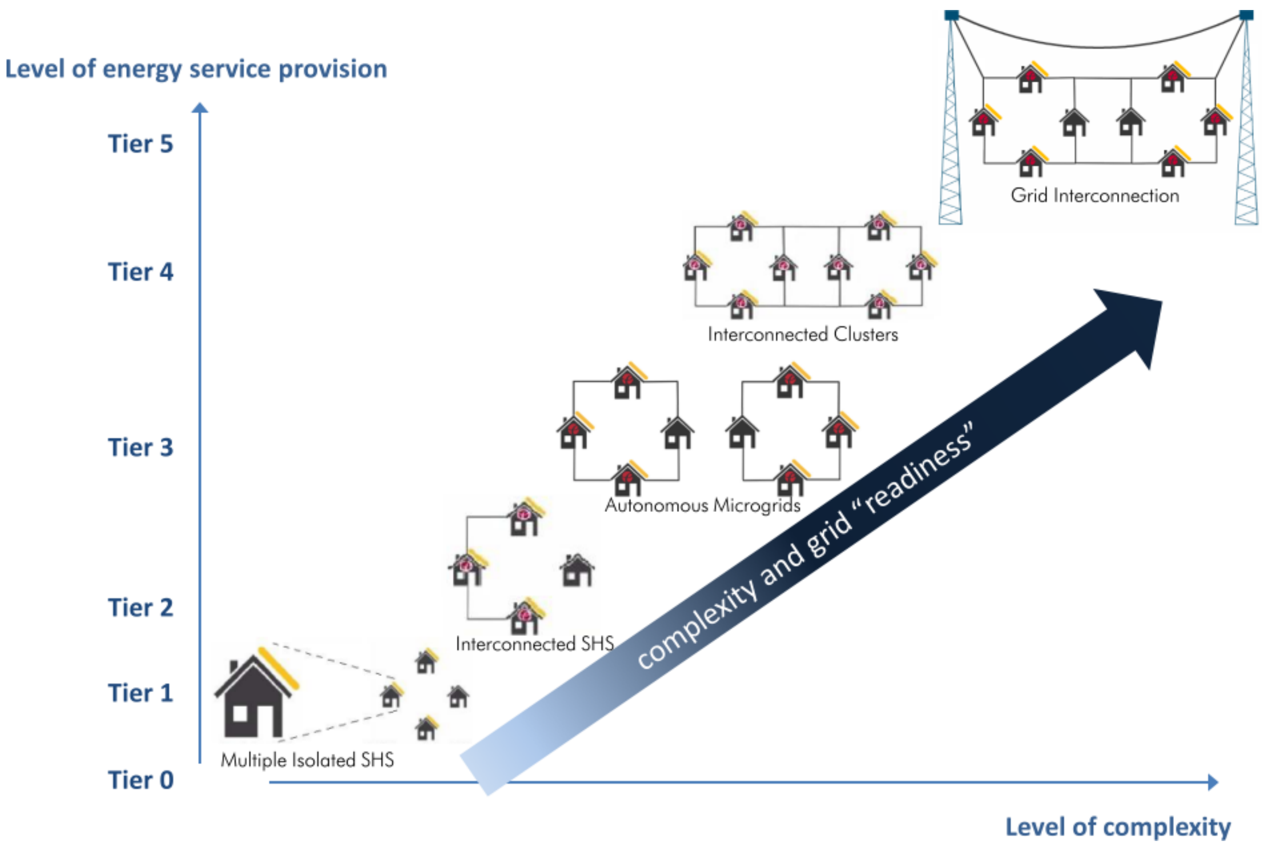

Figure 1.7: Electrification steps based on tier based service provisions and complexity. Source: Groh & Koepke, 2014

What seems misleading in figure 1.7 is the underlying assumption that the higher the degree of interconnection or the closer one gets to a national grid like infrastructure, the higher the level of energy service provision measured by a multi-tier framework. As a matter of fact, chapter 5 will prove this to be wrong. In order to reach universal electrification, Welsch et al. [2013] suggest that 'smart and just grids' will be needed. While a technical and functional definition of smart grids has yet to come, one can say that it *"encompasses a range of innovative tools, technologies and practices envisioned to be supported by novel business models and regulatory frameworks"* [...] to help ensure a reliable, secure and economically efficient supply of electricity services [Welsch et al., 2013, pg. 337]. Kolhe [2012] argues that from a Global North perspective smart grids will pave the transition process *"from a centralized producer controlled network to one that is less centralized and more consumer-interactive"* [Kolhe, 2012, pg. 88]. The same may apply to a developing country context with the difference that there is far less legacy infrastructure in place that needs to be transformed. The aim of smart grids is to intelligently integrate the generation, transmission and consumption of electricity. Some may argue that grid-readiness further forms part of a smart grid approach in order to avoid redundant energy infrastructure [Group, 2015; Economics, 2015]. Grid-readiness here means that a minigrid anticipates the arrival of the national grid and facilitates its interconnection, where retrofitting would be the costlier choice. Hvelplund et al. [2014] suggest expanding the term smart grid to smart energy systems as at times the most cost-effective solutions are found in combination with other sectors beyond electricity [Hvelplund et al., 2014]. This goes hand in hand with the recent trend in including the agricultural sector in minigrid designs with an emphasis on productive uses [Chapter 3]. A just grid or energy system, in turn, refers to the objective to not marginalize the poor. Welsch et al. [2013] conclude that 'smarter approaches' may enable countries in Sub-Saharan Africa to leapfrog traditional power systems in the short term and strengthen economic growth. Chapter 6 introduces and analyzes such a smarter energy system for the case of Bangladesh.

1.5 Research question, objective and outline of the thesis

The dissertation aims to study the role of innovative approaches in facilitating access to electricity in the context of energy poverty. It hereby addresses three overarching research questions that are rooted in the empirical challenges faced by the energy access sector:

i *What is the relationship between energy poverty, different forms of remoteness and its implications for the people's development opportunities?*

ii *How do we rate the proficiency to deliver energy service of different MES based on a multidimensional energy access framework?*

iii *To what extent can a smart design overcome the challenges currently faced by minigrids designed for rural electrification?*

A distinct set of methodologies is applied throughout the dissertation: Primary empirical data has been collected and analyzed for the development of chapter 2, 3 and 5. The thesis further makes use of micro-econometric modeling (Chapter 2), smart minigrid design (Chapter 3, 6), comparative analysis along multi-tier evaluation frameworks (Chapter 4, 5), advanced descriptive statistics and decision rule computation (Chapter 5), levelized cost of electricity and cost-benefit analysis (Chapter 6). All chapters aim to contribute to the three core questions mentioned above.

The following will shortly summarize chapters 2 to 8, including five scientific papers, researched, written and published -or in the process of- over the past three years that form the core of this dissertation.

Chapter 2:

The role of energy in development processes - The Energy Poverty Penalty: Case study of Arequipa (Peru)

The chapter empirically assesses and differentiates energy poverty from an end-user perspective. The energy poverty penalty (EPP) concept postulates that the energy poor spend more money on energy in both relative and absolute terms as they pay a poverty premium. An empirical analysis of 342 households and micro-businesses in rural Arequipa (Peru) finds statistically signicant evidence for the existence of the EPP while controlling for income and infrastructural poverty/ structural handicaps. The penalty is found to be most prevalent in the lowest income segments. These results lead to two implications: First, the deprivation of a certain level of energy service quality exacerbates poverty. Second, there is a clear indication of a uni-directional (or at least bi-directional) causality running from energy service quality to economic development.

Chapter 3:

Off-grid rural area electrification through solar-diesel hybrid minigrids in Bangladesh: resource-efficient design principles in practice

This chapter introduces the case of Bangladesh and the induced transition from a solar home system to a minigrid program. It shows how the SE4ALL goals can be translated into resource-efficient design principles. Emphasis is put on the electrification scope for productive uses through hybrid minigrids ranging from 100 to 250 kWp. These types of minigrids have yet to prove both scale and commercial viability. A possible pathway for the case of Bangladesh is elaborated herein with the help of several case studies. The chapter is very rich in local data and information based on multiple demand assessments and actual design experience. It results that a mutual pursuing of the SE4ALL goals is possible based on the suggested design considering a reliable energy access, high share of renewable energy in the energy mix and incentives for the use of energy efficient appliance technology.

Chapter 4:

The Battle of Edison and Westinghouse Revisited: Contrasting AC and DC microgrids for rural electrification

Chapter 4 expands more on the design question of minigrids taking reference to the oldest battle in the history of the provision of electricity: The Battle of Edison and Westinghouse. It asks the question how AC and DC microgrids can be contrasted in theory and practice based on their proficiency to deliver energy services. The intuitive hypothesis is that given that most of the distributed renewable energy (DRE) generators as well as batteries deliver DC power and that the majority of appliances being used in rural areas (can) run on DC, it follows that DC-based microgrids are a logical and efficient choice as a solution for electrification. The chapter runs a qualitative assessment based on a multi-tier approach for both options, as well as it analyzes at first hand the first DC-based microgrid in Bangladesh. It concludes that current trends in the energy access sector positively affect DC microgrids which also perform slightly better in a comparative analysis. The uptake of the same remains low though due to existing lock-in effects. These, however, do not occur based on prohibitive changing cost (greenfield energy access environment) but rather due to a lack of confidence and knowledge transparency of the alternatives.

Chapter 5:

> You are what you measure! But are we measuring it right? An empiric analysis of energy access metrics

Chapter 5 also uses the multi-tier framework but in contrast to Chapter 4, employs a quantitative approach to assess the proficiency of energy interventions to provide electricity services in Bangladesh. For this, a set of 231 questionnaires based on household and micro-business data is exemplarily analyzed to identify the missing links of present energy service offer to reach higher tier levels. It further performs a closer examination of the candidate multi-tier measurement tool for the global tracking framework of the SE4ALL initiative. The challenges in its application lie in reliable data collection, adequate gradation of indicators, and an effective algorithm for the tier assignment based on the specified set of attributes. The study showcases very high sensitivities to parameter changes, different algorithms, and data requirements. The results reveal a clear trade-off between capturing the multi-dimensionality of energy access and the simplicity of an easy to use global framework.

Chapter 6:

> Swarm Electrification - investigating a paradigm shift through the building of microgrids bottom-up

This chapter introduces a new model of bottom-up electrification based on the ideas of a smart and just energy system. The theoretical concept of swarm intelligence where each individual node brings independent input to create a conglomerate of value greater than the sum of its parts, is applied here to an alternative electrification scenario based on the example of Bangladesh. The chapter raises the questions of whether a grid can be built from the bottom-up in an economically sustainable way and whether such an approach can meet the challenges facing current trends in microgrids for rural electrification. It results that in certain rural areas the concept of swarm electrification may present a better fit to meet the combined goals of universal energy access for all and fostering rural economic development.

Chapter 7 and 8 conclude by summarizing the main insights in the form of a synthesis and presenting an outlook for further research.

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Chapter 2

The role of energy in development processes – The energy poverty penalty: Case study of Arequipa (Peru)

"In short, no energy means no development."

- Statement by European Commissioner Piebalgs on sustainable energy in Africa, Brussels, Feb 2014

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The role of energy in development processes—The energy poverty penalty: Case study of Arequipa (Peru)

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This paper empirically assesses energy poverty from an end-user perspective. The concept of an energy poverty penalty is developed arguing that people that are deprived of a certain level of energy service quality (e.g. lack access to the grid) spend more money on energy relative to their total income than people who enjoy better energy service quality. Additionally, it is tested whether these people also pay more in absolute terms given the same income level measured by asset indices. Both conditions are met in the analysis of a conducted dataset consisting of 342 households and micro-businesses in the rural area of Arequipa, Peru. Mobile phone network coverage is used as proxy for remoteness criteria and to build data strata, thus facilitating model replication for different geographical areas and a systematic measurement of structural handicaps. It is further shown that it serves as a better proxy for remoteness than the mere measure of distance to the capital. Income is proxied by two forms of asset indices further representing pure asset poverty and multidimensional poverty. The penalty is found to be most prevalent in the lowest income segments. The paper sheds light on the relationship between energy poverty, remoteness and implications for the people's development opportunities. The proof of the energy poverty penalty has strong implications for the present perception of energy poverty. Its existence raises questions on the impact of this penalty with respect to causing a trap that is delaying (rural) development at the household level or even prohibiting the development path. It leads to further discussion on the causality between energy service quality and economic development at low-income segments in a country.

Introduction

Recently, the UN General Assembly has declared the years 2014–2024 to be the "*Decade of Sustainable Energy for All*" (UN, 2013), underlining the importance of supporting the roughly 1.3 billion people living without access to electricity and nearly 2.6 billion being dependent on traditional biomass for cooking,[2] approximately 84% of which reside in rural areas (WEO, 2011, 2012). It is estimated that another billion are left with unreliable electricity networks (AGECC, 2010). This underserved population's energy service supply can be summarized with three main characteristics: poor quality, hazardous to health, and high cost. The term quality is used herein as the characteristics of a *product or service that bear on its ability to satisfy stated or implied needs* (ASQ, 2013). In this sense poor energy service quality can refer to insufficiencies, unreliability, dangers in usage, low durability, unfitness, lack of after-sales service and even non-affordability, in the sense of poor financial services. Many of these aspects are often interrelated.

The present paper builds upon the general idea that these kinds of shortcomings, referred to as the "poverty penalty", occur due to poverty and related structural handicaps[3] that result in the poor paying more than their wealthier counterparts for basic services (Prahalad and Hart, 2001). Literature often deals with energy poverty and although many ways to measure it have been introduced in the last decade, there is still no consensus on this issue (Nussbaumer et al., 2012). Currently, literature still lacks an in-depth and conceptual analysis on energy poverty through a rigorous and quantitative assessment. It does not adequately address structural handicaps in its assessment. Degree of remoteness seems to play a major role as it determines access to basic infrastructure and related cost for service delivery (Bird et al., 2011). Remoteness however, is not necessarily reflected by a mere measure of distance. This is particularly the case in areas with a high degree of topographical diversity (e.g. Peru). Within this paper the concept of an *energy poverty penalty* (EPP) is empirically developed taking into consideration different degrees of mobile phone coverage as a new proxy variable for distance. The EPP concept implies that poorer people tend to spend more on energy services in relation to their total income

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[2] The great majority of them use this biomass consisting of wood, animal dung and crop waste with open fires or leaky stoves causing almost two million people dying a year prematurely from illness (based on WHO 2004 data). http://www.who.int/mediacentre/factsheets/fs292/en/index.html.

[3] Throughout the text these structural handicaps are also referred to as deprivation of a certain level of energy service quality, physical and economic isolation from distribution systems and infrastructural poverty.

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than comparatively richer people.[4] This hypothesis is fairly intuitive, considering that people living in poverty are more likely to live off-grid, and alternative energy applications to grid-based power are usually much more expensive (DFID, 2002; Laufer and Schäfer, 2011; Sovacool, 2012). Additionally, Schäfer et al., 2011 refer to a low degree of adaptability of energy technologies to the people's specific needs and situations resulting in poor energy service quality. This frequently occurs because of an urban bias of energy service providers causing greater and more numerous expenses. If people that are deprived of good energy service quality (e.g. lack access to the grid) spend more money on energy relative to their total income than people who enjoy better energy service quality and also pay more in absolute terms when controlling for income, they are considered to be trapped by the energy poverty penalty. The EPP concept aims to enhance the understanding of the role that energy plays for people in remote areas living in poverty and its implied challenges for their development. We argue that the concept of the energy poverty penalty has important implications based on its adverse impact on sustainable development[5] for households and micro-businesses[6] in the low-income segment of a country. Following this argument, the energy poverty penalty gives room for the assumptions of previous authors that causality between income and energy access can indeed be bi-directional.[7] Previous publications state that causality mostly runs from income to energy access, albeit less commonly considered, energy access can also facilitate/increase income generation (WEO, 2010) and per se be a driver of economic development (Birol, 2007). This argument usually postulates a productive use of energy services, meaning that people have to use the improved energy services actively within their income generating processes. Generally agreeing on these issues, this paper takes a stand with the additional caveat that the poverty penalty trap inhibits or delays development irrespective of the way energy is used in people's daily lives and the associated implications on the causality debate at the micro level. Bhattacharyya (2012) restates the critical role played by energy in achieving sustainable development. As a consequence, better energy service quality could well serve as an essential tool to fight the energy poverty penalty and ultimately help achieve the Millennium Development Goals (MDGs) (UNDP, 2005; Kebir et al. 2013). Efforts to improve energy service quality, herein, are referred to as energy inclusion. *Energy inclusion* may be defined as a process of improving energy service quality for vulnerable and low-income groups (at an affordable cost)[8] and thus is in line with the goal of lowering energy deprivation as suggested by Nussbaumer et al. (2012) as opposed to mere access. While the majority of papers published in this field evaluate access to energy and adopt the sole perspective of the supply side (typical indicators are quantity of energy consumed and share of households with access to electricity), this paper takes the end-user perspective. This implies a measurement of deprivation/structural handicaps which reflects the demand side situation to a much better degree (Nussbaumer et al., 2012) and goes hand in hand with a concept of development understood as an expansion of capabilities (Sen, 1999). This distinction is important as it puts the energy poor household/micro-business in the center of the attention of analysis by assessing her energy situation and related opportunities/capabilities for development. Merely assessing supply/access ignores aspects of quality and cost and is misleading in the sense that it does not take into account the poverty penalty trap. To date, quantitative market research on the energy demand of rural populations has often been neglected due to the involved time, effort and related survey costs as well as previous inconclusive results (Kebir and Heipertz, 2010; Martinot and Cabraal, 2000). As a consequence, there is little empirical data dealing with the issue of energy poverty (Nussbaumer et al., 2012), especially regarding the role energy plays in development processes, e.g. poverty reduction efforts or development capabilities. For the present research data on 342 households and micro-businesses in the rural area of Arequipa (Peru) is collected. Peru is chosen for reasons of data access, interesting topographical features (as a part of structural handicaps) as well as its assumed potential for energy inclusion measures. The country exhibits a comparatively high human development combined with a very low energy development.[9] As such, development in economic terms seems to have already set in, whereas the energy development path lags behind. This mere observation speaks against the assumption of a causality running from income to energy service quality. But it also sets the tone for an urgent need to drive policy action toward an improvement of energy services, especially in the rural area where in Peru only 40% are electrified (ESMAP, 2010). Finding evidence for the EPP indicates that as a consequence of energy inclusion human development will also increase based on higher disposable income.[10]

The questions that remain in literature so far concern not only a bottom–up assessment of energy poverty but also the identification of possible turning points for the causality between energy service quality and development. While the first issue is dealt with in this paper, the second issue remains rather vague and left for further research. Pachauri (2011) states that reaching a consensus on the specification of energy access hinges on agreements on three elements: 1) consensus on services defining the basic needs basket, 2) a clear definition of the thresholds defining the basic needs, and 3) assessing the household expenditure on energy by different income class. This paper sheds light on the third issue by researching on energy poverty aspects of the rural Arequipan population with a focus on energy expenditure patterns including different income classes aiming for an empirical proof of the energy poverty penalty. It further deals with the relationship between energy poverty, remoteness and implications for the people's development opportunities.

The rest of the paper is organized as follows. The section on "Energy poverty" gives some concise insights on the current status of energy poverty research. "Methodology" describes the applied methodologies. "Descriptive statistics" presents the descriptive analysis whereas "Regression results and discussion" discusses the empirical results. The last section concludes.

Energy poverty

There is a range of articles summarizing the status quo of energy poverty literature. Nussbaumer et al. (2012), Sovacool (2012) and Pachauri (2011) give extensive overviews evaluating different approaches to measure energy poverty. Hence, this chapter merely tries to complement these articles where considered important for the presented analysis.

First, the numbers published by the IEA and cited in every publication on energy poverty, namely the 1.3 billion people lacking access to electricity and the 2.6 billion people dependent on biomass, not only ignore important aspects of quality (Nussbaumer et al., 2012), but also do

[4] Costs associated with adverse health impacts, wood fuel collections, among others, are beyond the scope of this work.

[5] Sustainable development is understood here as defined by Brundtland giving "overriding priority" to the needs of the poor (WCED, 1987).

[6] This paper follows the definition of Cull et al., 2006 who define very small (micro) enterprises, herein referred to as micro-businesses, as enterprises with less than five employees" (Cull et al., 2006, p. 3018).

[7] For an overview on the energy development nexus please refer to the review articles of Ozturk (2010) or Payne (2010).

[8] Technically this already forms part of a better energy service quality.

[9] Peru has a Human Development Index value of 0.725, as such belonging to the group of countries in the high human development segment; ranked 80 out of 187 (UNDP, 2012), whereas its Energy Development Index value in extremely low with 0,39; ranked 29 out of only 65 developing countries (IEA, 2012).

[10] Further dimensions of human development (e.g. health; education, access to information) are also influenced but could not be empirically evaluated within the scope of this paper.

not seem to consider the overlap between electricity access and biomass dependency. This overlap is calculated within this analysis. So far there is no distinction as to how many people are affected by only one or both of the access criteria. Detailed criteria defining dependency in the case of multiple fuel use, a major concern when it comes to the literature on energy ladders (Sovacool, 2012), are equally lacking. The oft-stated number of a billion people with intermittent supply seems very low and a clear basis for calculation remains undefined.[11]

Second, composite indices, such as the Energy Development Index (WEO, 2010) or the Multidimensional Energy Poverty Index (Nussbaumer et al., 2012) are very good complementary tools for benchmarking performance. However, they provide only limited insights on what constitutes energy poverty and its implications in economic terms (e.g. expenditure data). The latter issue is addressed herein as it is considered key when studying the issues of the energy poverty penalty and its potential impact on development opportunities.

Third, there is a range of articles stating that the poor in particular spend large amounts of their income on energy and from there conclude that there is a big savings potential shaping the path for energy inclusion measures (e.g. DFID, 2002; Hussain, 2011; Kebir and Philipp, 2004; Masud et al., 2007; Sovacool, 2012; UNDP, 2003; WHO, 2006). These quantitative assessments either focus on the comparative unit cost of energy versus grid prices, e.g. USD 1.50 per kWh in rural Bangladesh (Kebir and Philipp, 2004) or on their expenditure as a percentage over total income which can range up to 80% in extreme cases (Masud et al., 2007). The numbers per se, however, do not provide adequate insight on the severity of energy poverty and lack of systematization. Accounting for structural handicaps in the EPP model aims to put these insights into a conceptual framework. Barnes et al. (2005) build upon this data and define a threshold, that if energy expenditures as a proportion of total income are greater than 10%, people are considered energy poor. Khandker et al. (2012) refine this approach arguing that the threshold point at which energy consumption begins to rise with increases in household income manifests energy poverty. Below that point people are assumed to consume the bare minimum and thus are considered energy poor. Krugman and Goldemberg (1983) raise the issue of minimum threshold energy and determine ~45 GJ/year as an acceptable level for development for Latin America, Africa and Asia. Pereira et al. (2011) set the poverty threshold for 10 GJ/year focusing only on rural households based on a survey conducted in Brazil. Steinberger and Roberts (2010) analyze the relationship between primary energy consumption and the Human Development Index (HDI) detecting a decoupling effect with increasing energy consumption. Moreover, they point out a non-linear relationship with the observation that for poor countries great advances in human development tend to come with relatively slight increases in energy consumption. The authors conclude that development tends to be comparatively "energy cheap" at this stage. Looking at it differently would suggest the following. We assume that with a better energy service quality, the actual energy consumption does not necessarily need to increase a great deal for energy poor people, because everybody consumes energy in the first place whether s/he has access to the grid or not. At these stages it is a matter of quality. Alternative sources can range from kerosene lamps, car batteries to diesel generators for both as alternative electricity source or back-up solution in case of frequent brown-outs. Nontheless, with better energy service quality energy consumption will eventually increase and human development will experience a disproportionate increase. Therefore, depending on causality, one could equally argue that energy inclusion measures are an effective way of increasing human development. The causal effect however, may have a time lag.

[11] This sector of people with intermittent electricity supply may be referred to as temporarily off/on-grid sector. There is a need for further research investigating distinct degrees of deprivation of a certain quality of electricity supply among this group of people.

Steckel et al. (2013) argue that having observed minimum energy thresholds, climate policy action which is leading to lower energy consumption levels can in fact bear the risk of a poverty trap[12] that might inhibit or delay people's development path. Prahalad and Hart (2001) introduce the concept of the poverty penalty caused by the fact that poor people are often physically and economically isolated from distribution systems forcing them to pay a poverty premium. This premium usually consists of higher and more frequent expenses considered a penalty caused by poverty. In 2004, the WEO for the first time referred to energy poverty as one factor of poverty traps. This paper picks up on these ideas of poverty penalties developing the assumption that low quality energy services put a penalty on some of the poor. A recent article calls the poverty premium into question finding opposing results[13] in a study comparing consumer good prices in Dharavi slum and central Mumbai (Kay and Lewenstein, 2013). They claim this false belief as a major reason why many companies targeting the base of the pyramid fail, among them energy inclusion measures. Irrespective of the opposing results for the urban slum area, it is argued here that physical and economic isolation from distribution systems in rural areas are structural handicaps rooted in degrees of remoteness and economies of scale. The present paper is set on these issues by developing the concept of the energy poverty penalty in rural areas. A bottom–up approach is developed contrasting previous research on aggregated country specific indicators or indices.

Methodology

In order to build a systematic framework for the EPP, a number of methodological steps have been performed. First, we designed a questionnaire based on the key outcome which is an assessment of energy poverty in terms of a disaggregated measure of energy expenditure, household and micro-business' income as well as structural handicaps. Further, a specific sampling technique is applied to ensure representativeness. Based on the collected data in the field, an asset index is developed for an adequate measure of income. The asset index is then used for a clustering of the dataset into more homogenous sub-panels. Based on these steps, finally, a descriptive and regression analysis is performed for further inference. Each step is discussed below in greater detail under the respective section.

Questionnaire design and sampling technique

The field research is performed in the Arequipan rural area. The research includes an observational sheet for village profiles and a questionnaire for rural households and micro-businesses (see Appendix A Questionnaires), which are designed in line with Sen's capability approach (Sen, 1999). Thus, data collection does not only focus on expenditure but also collects information on energy access opportunities, choice sets and energy service quality. Income data is assembled through an asset index. The term *energy*, due to its intangibility, has not been mentioned in any question of the questionnaire, but rather inquiries on specific sources, appliances and energy service quality, as well as opportunity costs, run throughout. The questionnaire design gains considerably from an example set-up by ESMAP[14] for the Peruvian rural area. However, the ESMAP (2010) survey lacks certain characteristics which we attempt to correct for. First, it makes no distinction between households and micro-businesses (addressed in Q12f.), but merely focuses on household energy expenditure. Second,

[12] A poverty trap is "a stable steady state with low levels of per capita output and capital stock; […] if agents attempt to break out of it, the economy has a tendency to return to [it]" (Barro and Sala-i-Martin, 2004, p. 74).

[13] E.g. Prahalad and Hammond (2002) state poverty premium from 1.2 to 57 times the prices of Dharavi slum to the same comparison area. Agnihotri (2012) claims prices ranging from five to twenty-five times above the normal retail prices.

[14] The Energy Sector Management Assistance Program (ESMAP) is a global, multidonor technical assistance trust fund administered by the World Bank.

it lacks the simple and lean approach and is thus too time-consuming for the interviewee, potentially leading to a bias. Furthermore, this study will also extract observational data, which the ESMAP survey failed to consider (see Q.27ff). The short and simple design of the questionnaire is considered very important to ensure a high number and quality of responses.

For the sampling technique, it is noted that the region of Arequipa exhibits a huge geographical diversity of topographical and climatic differences, which have different impacts on energy usage behavior. In order to account for these topographical differences, when discussing issues of remoteness, it is possible that measuring mere distance does not suit the purpose here. Therefore, mobile phone network coverage data is analyzed. There is a strong debate on the relationship between rural mobile phone coverage and rural economic development.[15] There is likewise a debate on the relationship between rural electrification rates and rural economic development.[16] In both cases the majority of the papers come to the conclusion that there is a positive correlation, although the question of causality remains unresolved. Nevertheless, it can be stated that regions with different levels of mobile phone coverage usually differ in certain characteristics, primarily degree of remoteness, population density and/or economic development. Establishing a link between electrification rates and mobile phone coverage leads to an interesting analysis due to the fact that mobile phone penetration in regions without access to electricity requires alternative energy service provision for mobile phone charging. Research performed by Buys et al. (2009) and Aker and Mbiti (2010) indicates that mobile phone coverage is strongly dependent on factors such as population density, per capita income and topography (higher elevation, steeper slopes, and distance from a main road and major urban centers), all showing negative correlation results and some kind of measure of structural handicaps as introduced earlier.

Therefore, mobile phone network[17] coverage is used herein to generate data stratification. It is assumed to exhibit the unique characteristics mentioned above and thus enables a clustering of all villages according to the penetration of the mobile network market. Hence, different degrees of mobile phone coverage are used as a proxy for remoteness. A set of 3356 villages of the region of Arequipa is divided into four categories.[18] The division results in a list of four different levels:

1st level coverage by all three providers: 86 villages

2nd level coverage by only two of the three: 565 villages
3rd level coverage by only one of the three: 491 villages
4th level coverage by none of the three: 2214 villages

In order to guarantee a randomized sample, each level's villages are sorted randomly and then drawn with a skipping pattern. A skipping pattern of ten leads to a sample of eight 1st level villages, a pattern of 50 to ten 2ndlevel and nine 3rd level villages, and, lastly, a pattern of 200 to twelve 4th level villages. Different skipping patterns were used in order to have an approximately equal number of villages from each category.

Thus, a total of 38 villages constitute the sample for the village profiles (see Fig. 1 for the GPS tracking in Appendix B). The green spots indicate the villages visited during the field study. Villages are well distributed over the region. Nine households/micro-businesses[19] are selected randomly in each village for interviews leading to a total sample of 342 questionnaires from 32 out of 109 existing districts and in seven out of eight provinces of the region of Arequipa, Peru. In cases where the sample villages cannot be used due to a variety of reasons,[20] the nearest village with the same mobile coverage level is chosen. For an overview of provincial representation please refer to Table 1 in Appendix C. This step is crucial for two reasons. First, it gives a high probability of having a representative panel in terms of structural diversity. Second, it later on allows an in-depth analysis based on the same structural diversity.

Asset indexing

Generally speaking, income is the choice when it comes to the measurement of living standards in developed countries, whereas in a developing country setting the preferred metric is an aggregate of households' consumption expenditure (Sahn and Stifel, 2003). The latter is preferred for a range of reasons, chief among them the seasonal variability of earnings and the high percentage of self-employment, not accounting consumption of self-produced good as income. In any case, collecting reliable income or expenditure data is an extremely difficult task, especially in case of resource limitations. For this reason, rather than income or expenditure, in this study data is collected that captures living standards, such as ownership of durable or productive assets (e.g. electronics or animals), infrastructure (e.g. access to drinking water, electric grid), and housing characteristics (e.g. number of rooms, source of drinking water, type of bathroom). This asset-based approach has been implemented by previous authors.[21] Instead of constructing the asset index with simple weighted average of proportion of households that own individual durable goods[22] as proposed by Wang and Wang (2003), the weightings are obtained through principal component analysis (PCA), as introduced by Hammer (1998) and Filmer and Pritchett (2001). PCA is relatively easy to compute and more accurate than using weighted averages.[23] The intuition behind PCA is that there is a latent variable, in this case material welfare that manifests itself through the ownership of different assets (durable goods; housing conditions, level of education):

$$assetind_i = \propto_1 * a_{i1} + \propto_2 * a_{i2} + \ldots + \propto_k * a_{ik} \tag{1}$$

$$a_{ik} = \beta_k c_i + u_{ik} \tag{2}$$

for I = 1,…N households/micro-businesses and k = 1,…K assets. *assetind* is the asset index for each household/micro-business, the *a* refers to the respective asset evaluated as a dichotomous variable, whereas the weights that are used for aggregation to a one-dimensional index are represented by α. The weightings follow a highly intuitive pattern. If a wealthy household has a radio and a computer, and all other households also have a radio, the distinguishing factor is the computer and as such receives a comparatively higher weight than possession of a radio. Moreover, the appealing nature of this approach to estimate wealth is that if a certain asset addressed within the survey has a high correlation with owning other assets that were included in the questionnaire, it is also likely to be correlated with the ownership of other types of assets that were not in the survey (Moser and Felton, 2007).

[15] See Bhavnani et al. (2008), Donner and Escobari (2010), Aker and Mbiti (2010) and Aker and Fafchamps (2011), among others.
[16] See Cabraal et al. (2005), Bhattacharyya (2006), Das (2006) and Cook (2011), among others.
[17] From here on simply referred to as mobile phone coverage, not to be mistaken by physical possession data of mobile phones by the people.
[18] There are only three mobile phone providers active in Arequipa: Movistar, Claro and Nextel. Data was obtained via OSIPTEL (Organismo Supervisor de Inversión Privada en Telecomunicaciones), a public entity responsible for the supervision of the telecommunication sector, with data publicly available under: http://www.osiptel.gob.pe/coberturamovil/.
[19] Often referring to mixed entities in the sense of micro-businesses. Every household head is asked whether s/he is selling any goods from his private house which usually results in a mixed accounting scheme of private and business income and expenditure.
[20] Non-existence, total population lower than nine, village as mining industry settlement, village only consisting of off-season fincas, and village being too difficult to access.
[21] Please see (Sahn and Stifel, 2003; Moser and Felton, 2007; Young, 2010; Harttgen and Klasen, 2012) for more information.
[22] In this case the asset index is a simply a monotonic function of all arguments included which is an arbitrary assignment of equal weights and can take the following form: asset_index = $0.2 * X1 + 0.2 * X2 + 0.2 * X3 + 0.2 * X4 + 0.2 * X5$.
[23] A factor analysis could also be employed in this case but usually shows very similar results (Sahn and Stifel, 2003).

Moreover, since durable assets are taken into consideration, the risk of measuring the impact of only a short-term shock is considerably reduced. Also, since only rural households are in the sample, the relevance of certain variables (e.g. agricultural land size) is expected to be relatively even. However, three points of concern which could potentially lead to a biased asset index should be expressed here. First, the conducted survey does not take into account the quality or age of the respective assets. As such the value of some assets might be overestimated and others comparatively underestimated (e.g. no difference made between b/w and color TV). Second, there is no distinction made between a pure household's asset index and one for a micro-business which also potentially leads to biased results.[24] And third, the provision of some assets (such as toilet type) could be a result of local NGO activities and consequently not reflect an income-based measure of prosperity.

Two different types of asset indices are constructed for reasons of comparison, sensitivity analysis and later to be able to construct an instrumental variable. Three different groups of physical, productive and human capital are defined as indicated in Table 2 in Appendix C. Taking all variables into consideration, the first version represents a multidimensional index and is from here on referred to as *multidimensional poverty*. The second asset index consists solely of durable assets, and is referred to as *asset poverty*. Both poverty indices exhibit higher poverty if their index value is lower. Note that from the collected data neither energy expenditure nor access to the grid data is considered for the construction of the asset index, so it can be used in the regression analysis. Three different types of discrete data are produced in the case of the first asset index: count data (e.g. number of windows), nominal data (e.g. toilet type) and ordinal data (e.g. degree of education). To be able to work with the data, different methods are proposed in literature. Two different approaches are applied for the construction of the first asset index via principal component analysis: the Filmer–Pritchett-Procedure and Polychoric Correlations. Filmer and Pritchett (2001) suggest generating dummy variables for each of the categories of the discrete ordinal data. Following this approach the principal component analysis results in 16 components as per the rule of thumb to have associated eigenvalues greater than one. This constellation results in a rho of 0.7054. Due to the amount of variables and components, the actual asset index is constructed through the PCA prediction function and summed up with the weightings according to the explaining power of each component. The advantage of this method is that it imposes very few assumptions on the data (Kolenikov and Angeles, 2005). Conversely, the developed order of the ordinal variables gets lost. Further, the data now suffers from the introduction of extra correlations through the generation of multiple dummies and thus negative correlations are produced between variables from a single ordinal source variable. In order to avoid the generation of multiple dummies, polychoric correlations can be used. These correlations go back to Pearson (1901) and Olsson (1979) and consist of a technique to run the estimation based on ordinal variables. Using this method, nine components result having an eigenvalue bigger than one and cumulatively explain 95% of the latent variable. However, data does not conform well to the assumptions of the polychoric PCA method. As different variable types are used, the underlying bivariate normality is not satisfied and consequently too many missing values are generated which cannot be solved by variable recoding.

For the second asset index only discrete data applies. In this case it is constructed using Multiple Correspondence Analysis (MCA), a technique related to PCA, but more appropriate here where the variables are not continuous or normally distributed. The kernel density estimations of the resulting asset indices are presented in Fig. 2 below. As stated, higher values of the asset index indicate lower degrees of multidimensional and asset poverty, respectively. The asset poverty curve clearly exhibits fat tails, especially for higher values of assets. It has higher standard deviation and more distinguishing power. The multidimensional poverty, in turn, complies fairly well with the assumption of a normal distribution.

Comparing the asset index of the on-grid and off-grid sample supports the hypothesis that off-grid people tend to be asset poorer (and also multidimensional poorer). The same applies for further remote people proxied by different levels of mobile phone coverage (see Fig. 3 below). As expected, both relationships indicate people living in areas with poor infrastructure are usually also poorer in terms of asset possessions.

Clustering

In order to generate more homogenous sub-panels, a clustering method is performed over different income classes along the asset index. The k-means method partitions the observations into clusters in which each observation belongs to the cluster with the nearest mean (Bacher et al., 2010). As an alternative the Wards linkage method is applied. The latter method results in very high number as an optimum cluster number, which leads to prohibitively small sub-sample sizes. For the k-mean method the number of clusters is an input parameter. For reasons of sufficient sub-sample size, the cluster number is fixed to three clusters. Table 3 in Appendix C exhibits the respective cluster results. Three income classes are distinguished and a multivariate test on significant differences in means can be confirmed at the 1% level means for all three classes. The clustering over income is important for the analysis of the EPP in different income segments of the overall panel.

Regression analysis

A linear regression model is constructed and the ordinary least square (OLS) as well as a two stage least square model (2SLS) is used as linear approximations for the analysis of the data. The OLS regression models take the following form:

$$\begin{aligned} \textit{relative energy expen}_i = {} & ß_0 + ß_1 \textit{electricity} + ß_2 \textit{microbiz} \\ & + ß_3 \textit{energy poverty} + \ldots + \varepsilon_i, \end{aligned} \tag{I}$$

where:

$$\textit{relative energy expen}_i = \frac{\textit{total energy expen}_i}{\textit{asset index}_i},$$

for i = 1,…N households/micro-businesses. *relative energy expen* stands for a household's/micro-business' monthly expenditure on energy sources, *energy poverty* represents variables such as biomass dependency, access to credit, degree of remoteness, energy security and quality, *microbiz* as a dummy for the status of a micro-business, among other variables. *total energy expen* represents total energy expenditure per month and is calculated through the sum of expenditures on electricity, gas, wood, kerosene/petroleum, small batteries, car batteries, photovoltaic, among others. For the calculation of the relative expenditure on energy both variables are standardized over mean of 100, so no negative values remain and a better representation becomes possible. All regressions are tested with robust standard errors in order to allow for heteroscedasticity.[25]

With the model the influencing factors that constitute energy poverty are tested. Electricity is a binary variable and is defined to be 1 in case of access to the grid. Hence, if β_1 turns out to be negative and significant, people who are deprived of this service, spend more on energy relative to their total income than people who have access (model I).

[24] E.g. A small internet shop certainly has a great deal of digital assets.

[25] With an exception for regression model V, where sub-panels are applied, the Breusch–Pagan/Cook–Weisberg test is performed (see Table 15 in Appendix C) and below for the model specification.

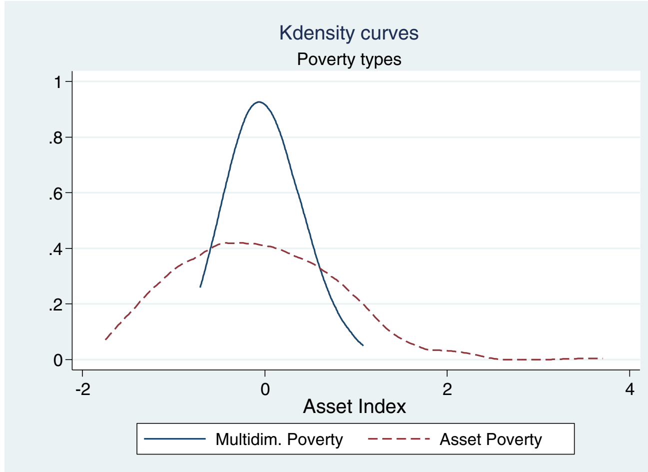

Fig. 2. Kdensity curves for asset indices.

A further modification takes into account that so far it is not clear whether increased energy expenditure or the lower asset index is the driver of the higher relative energy expenditures. Following the 2SLS methodology, an instrument is constructed representing infrastructural poverty/structural handicaps, a part of the differences between the multidimensional poverty and the asset poverty index.

The 2SLS model takes the following form:

1st stage:

$$non_{asset}poverty_i = \pi_0 + \pi_1 source_{drinking}water + \pi_2 cook_{source} + \varepsilon_i \quad \text{(II)}$$

2nd stage:

$$\begin{aligned} relative\ energy\ expen_2 i = \beta_o + \beta_1 electricity + \beta_2 credit + \beta_3 microbiz \\ +\beta_4 distance + \beta_5 non_{asset}poverty + \mu_i \end{aligned} \quad \text{(III)}$$

In order for drinking water and cooking source to serve as good instruments, they need to be uncorrelated with energy expenditure over asset poverty (*relative energy expen_2*), but correlated with the multidimensional poverty index. Only the variables mentioned above fulfill these criteria as can be seen in Tables 4 and 5 in Appendix C. Relevance of the instruments is given at the 1% significance level. The Hansen J test statistic, examining over identification, indicates that the instruments are appropriately uncorrelated with the disturbance process. Controlling for infrastructural poverty may reveal that higher relative energy expenditures are in fact determined by higher total energy expenditure, in case electricity continues to be significant and the instrument turns out to be insignificant.

Therefore, a further OLS model based on total energy expenditure is tested taking the following form:

$$\begin{aligned} total\ energy\ expen_i = ß_0 + ß_1 electricity + ß_2 microbiz + ß_3 assetindex_i \\ +\beta_4 \ldots + \varepsilon_i \end{aligned} \quad \text{(IV)}$$

If in Eq. (V) *electricity* equally turns out to be negative and significant, the sample group also spends more on energy in absolute terms holding all other variables constant (incl. the *assetindex_i*). If both conditions apply (Eqs. (I)/(III) and (V)) the energy poverty penalty is considered as proven.

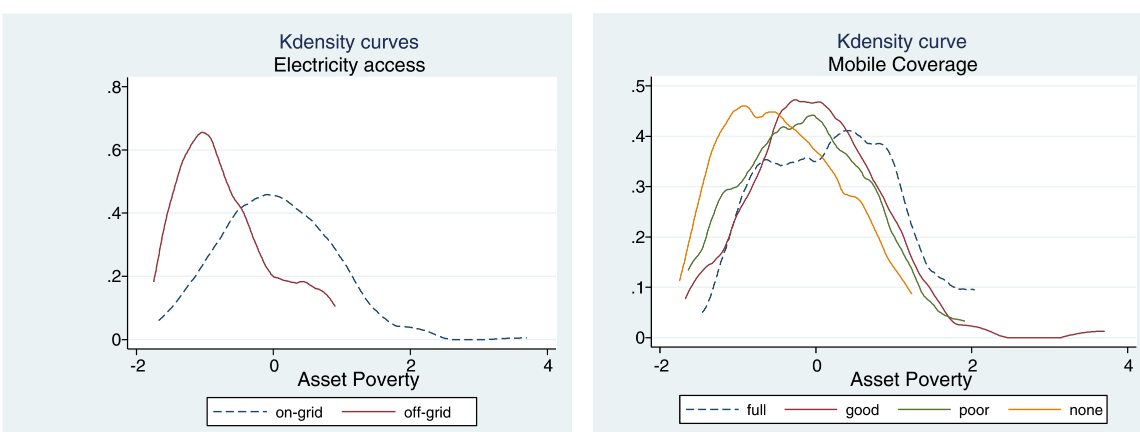

Fig. 3. Poverty and electricity access/mobile coverage.

In order to see whether the EPP applies also for sub-set of the panel, a further modification is tested based on different income classes:

$$total\ energy\ expen_{ij} = ß_0 + ß_1 electricity + ß_2 microbiz + ß_3 assetindex_i + \beta_4 ... + \varepsilon_i, \quad (V)$$

for j = 1, 2, 3 indicating the poorest, 2nd poorest and 3rd poorest income classes within the panel.

Descriptive statistics

Descriptive statistics are based on a randomized sample of 342 questionnaires from 32 out of 109 existing districts and in seven out of eight provinces of the region of Arequipa, Peru, as discussed in the previous section.

Household versus micro-business

The questionnaire aims to distinguish between pure households and mixed entities of households and micro-businesses, simply referred to as micro-business. As such, each person interviewed is asked whether any goods are sold from the house. Out of the total sample of 342 persons interviewed, 44% claimed to be a micro-business. 51% claimed to be a pure household, whereas 5% were undecided. There are no small enterprises in the sample.

Off-grid population and dependency on biomass

In the established sample, slightly more than 18% (62 observations) do not have access to electricity and 82% claimed to have access. This is a slightly higher number without access compared to the officially estimated statistics for total Arequipa of 14.8%. There are no official statistics available that state the number exclusively for the rural area. Since the sample is entirely rural, the higher number comes as no surprise, and is potentially even greater. With respect to the dependency on biomass, 32% use fuel wood as their only cooking source and another 7% use wood as their major cooking source in case of mixed use patterns (use of wood and another source at the same time). Considering the use of dung as the only cooking source (1.5%) and major source (2.6%), respectively, these numbers account to roughly 43% of all people interviewed depending on biomass for cooking purposes. This sample percentage is double the total official statistical Arequipan average of 21.8% of people being dependent on biomass. Considering the adverse health effects of indoor pollution, there is an urgent need for clarification of this apparent gap between sample and official statistical average. Twenty percent of the people using fuel wood also pay for it. Average monthly expenditure in this case amounts to S/.64 per month.[26] This is an extremely high value and indicates potential for a market-based intervention (e.g. through a microfinancing scheme). In order to rule out the possibility that there is no wood workshop in the dataset leading to exuberant wood expenses (there is only one observation indicating to the use of wood for work purposes without any value assigned). Also the higher values are double checked with respect to irregularities. The highest value of S/.300 is a restaurant probably using the wood for commercial cooking purposes, although it was indicated that it was not used for the business (potentially wrong answer in the questionnaire). Still the remaining sample size here is limited to 42 observations, so the issue needs further research. For 80% of the respondents who use fuel wood, but do not pay for it, data is collected on their opportunity cost indicated by the time spent to collect the fuel wood. On average, people collect wood fuel 7.28 times a month and need for the collection process on average about 5-1/2 h. Calculated more precisely by multiplying the hours indicated for wood collection by the number of times wood is collected per month for each observation, people spend on average about 30.66 h a month on wood collection, smoothed over the month approx. one hour a day. More than 50% of the sample perceives a decrease in tree population. For 36% it is now more difficult to find fuel wood and for another 10% it is partly more difficult. However, so far, 75% do not see rising fuel wood prices. If deforestation goes on, opportunity costs and fuel wood prices will eventually rise and more pressure is put on the rural biomass consumption pattern.

A rough percentage of illegal electricity access is calculated by dividing the number of people who do not have a meter by the number of people stating they have access to the public electricity network. According to this indicator, almost 13% have illegal access at their disposal. What needs to be distinguished here is the group of people who lack access because their whole village has no access (63%) and a mixed group of people lacking access although their village as such is connected (37%). Furthermore, people are asked for reasons why they do not have access to the grid. While only 5% of the people state that the reason is that there is no grid nearby (then it would be a result of remoteness), 60% of the people state the reason that the connection fees are prohibitive.

Concerning the previously raised issue of the intersection between these two indicators, this sample shows a 100% overlap; all people that reported a lack of access to electricity are also dependent on biomass. Among the off-grid population, 73% fully depend on wood fuel, 13% use wood as their major cooking source and the remaining 14% use dung.

Remoteness

The means of the distance from each village to the capital for off-grid and on-grid people are compared and reveal no significant difference. Since the general understanding in literature is that more remote areas are less likely to be connected to the grid, it seems that measuring mere distance is not sufficient in order to capture all dimensions of remoteness. This observation seems to apply particularly in the case of Arequipa due to its high degree of diversity with respect to climate and topography. The measured distance in km often differs substantially as a proxy for distance traveled and especially time and effort taken. Therefore, mobile phone coverage is introduced with the assumption of being more suitable as a proxy for the degree of remoteness. Mobile phone coverage is ordered from one to four indicating from very strong to no coverage dependent on the number of providers covering the respective place. It turns out that there is significantly lower (at 1% level) mobile phone coverage for the off-grid population compared to the on-grid population. This, in turn, tends to confirm the hypothesis that in the given context mobile phone coverage is better suited as a proxy variable than mere distance.

Energy service quality

On average people suffer from electricity cuts 1.5 times a day with an average length of 10 min. In order to assure the accuracy of this data, it is also asked how many days a week a household is left without electricity. The average also amounts to 1.5. The reason for these inconsistencies is that the outages heavily depend on the respective seasons (e.g. rainy or windy seasons cause more frequent and longer outages). Forty percent indicate that they are strongly or very strongly affected by these outages, whereas 14% were not affected and slightly over 20% did not know. Among micro-businesses, the perceived impact is slightly higher with more than 45% considering the impact as strong or very strong. Considering the type of outages it can be stated that about 85% of the cuts are unpredicted. Only 10% of the people stated that the outages are announced in advance. In

[26] USD 1 is equal to S/2.7 (as of May 15 2013; http://www.oanda.com/lang/de/currency/converter/)

the observational sheets it is indicated that people suffer most from broken electrical appliances due to overvoltage whenever the electricity kicks in again. Since the service structure for repairs is perceived as very weak, people often have to buy new appliances. One household has a sensitizer at its disposal guaranteeing the security of its appliances. However, the majority is not aware of the existence of such devices. It is important to note that electricity expenditure accounts for only 54% of total energy expenditure in the sample, and when taking out observations which indicate that they do not spend anything on energy apart from electricity (unrealistic assumption), the percentage goes further down to 39%. This is line with previous results stating that electricity forms only a minor part of total energy costs for the case of India (e.g. Bhattacharyya, 2006). This, in turn, requires a more detailed empirical analysis on the energy service quality, as described earlier, outside mere electricity outages, although this goes beyond the scope of this paper.

The energy poverty penalty (EPP)

It is assumed that people living in areas without access to the electricity grid often are forced to pay a poverty premium since they live in areas that are physically and economically isolated from distribution systems (Prahalad and Hart, 2001). This isolation implies higher efforts (directly monetary as well as through opportunity cost) for the same services. In the energy case two opposing effects can be observed. First, previous analysis has shown that they pay several times more for the same unit of energy than people living in on-grid areas (e.g. Hussain, 2011).[27] Consequently, this ‘penalty’ implies that they have to pay more for their energy services (effect of price). Second, it can be generally observed that consumption increases with income (also the case within this sample as seen above). As such, poorer people are expected to use less energy (effect of quantity). In the case of energy, however, and also in other cases, there is a subsistence minimum of energy services needed. Hence, the hypothesis is posited that poorer people spend more money on energy relative to their total income and also in absolute terms when controlling for income. If both conditions apply, it is referred to as *energy poverty penalty* (EPP).

Table 6 hereafter compares relative energy expenditure as the ratio of energy expenditure over income (proxied by the asset indices) as well as total energy expenditure for both people living on-grid and off-grid.

The difference in means in both cases indicates more expenditure for off-grid people despite the fact that on-grid people are asset richer on average and thus are expected to spend more on energy.[28] However, only the mean difference for the relative energy expenditure turns out to be significant (at 1% level). Furthermore, the numbers need very careful interpretation due to low sample size for the off-grid sector and very high values of standard deviation. Still, the numbers speak at least in favor of the existence of an EPP. Taking a closer look via graphical analysis confirms these observations (see Fig. 4 below). Again, off-grid people have higher relative energy expenditures. People with low asset and multidimensional indices (indicated by lower values) also have higher relative energy expenditures indicated by the negative slope. This is due to the fact that the asset index is on the x axis as well as in the denominator of the y axis.

Table 6
Absolute and relative on- and off-grid energy expenditure.

Variable	Obs	Mean	Std. dev.	Min	Max
Total energy expenditure					
Off-grid	42	84.84	129.64	1.5	540
On-grid	274	83.29	84.89	2.6	611.7
Relative energy expenditure					
Off-grid	38	1.008	0.015	0.987	1.059
On-grid	245	0.999	0.012	0.964	1.052

Abolute numbers reveal related inference. The slope turns positive due to the income effect of richer people spending more, including on energy. If, however, a household/micro-business lives off-grid, it has to spend more on energy than on-grid households/micro-businesses given the same income level (see Fig. 5). Therefore, graphical anylsis indicates the existence of an EPP. It is further shown that total energy expenditure varies drastically over different income levels. This might be attributed to the low sample size of the rural portfolio but can also lie on the fact that the EPP takes different forms for different income levels.

Regression results and discussion

The following discussion of the results follows the methodological sequence of the five displayed models as discussed in “Regression analysis”. The outcome of regression model (I) is given in Table 7 below. The first OLS modification gives rather inconclusive results and does not show significant results for access to electricity. Running the Ramsey RESET test[29] reveals that both modifications suffer from omitted variable bias (OMV), as the hypothesis that there is an OMV cannot be rejected (see Table 8 in Appendix C). Calculating the variance inflation factor for each independent variable indicates issues of multicollinearity for the variable population density.

In Table 9 below further specifications of regression model (I) are tested. Specification (1) and (2) aim to account for the problem of multicollinearity leaving out various independent variables. Specifications (3) and (4) target the issue of OMV including a range of new asset variables. For all specification no multicollinearity can be detected but specification (3) and (4) fail to fully solve the OMV (see Table 10 in Appendix C).

The first condition is met by the negative and significant coefficient of electricity at the 1% level for specification (1), 5% level for (2) and 10% level for specification (3) (although the OMV still remains). For the first specification the coefficient of electricity also turns out most relevant (standard deviation of the dependent variable here is 0.01). Note that electricity is less significant (and less relevant) when it comes to asset poverty, but more when multidimensional poverty is taken into account. These results seem to indicate that access to electricity is not only correlated with better assets, but even more strongly correlated with a better multidimensional poverty situation. This is most likely due to its correlation with other infrastructural variables which are represented only in the muldimensional poverty asset index. This assumption gains support looking closer into specification (3). It shows that variables such as type of bathroom (dummy 1 if flush, 0 if no flush) and location of bathroom (dummy 1 if outdoor, 0 if indoor) representing poor infrastructure also increase relative energy

[27] This needs further investigation if people who live literally next to the grid (but without being actually connected — illegal access is yet another case) also live in a high-cost eco-system. The earlier cited article from the Harvard Business Review contradicts this hypothesis for an urban slum in Mumbai (Kay and Lewenstein, 2013). Sovacool (2012) claims the opposite for the case of energy and refers to a special issue of Energy for Sustainable Development dated December 2008 for further proof on this matter. Within this paper the sample size distinguishing these two different types of off-grid population is too small for inference. The only indication which can be given at this stage is that connection fee often is an issue keeping people off-grid although it might be more cost-effective to be on-grid but initial investment is prohibitive.

[28] In the case of the absolute values a single outlier of S/1,534 energy expenditure has been taken out.

[29] The Ramsey Regression Equation Specification Error Test (RESET) tests the significance of a regression of the residuals on a linear function of least-squares estimates of the dependent variable (Ramsey, 1969). If non-linear combinations of the independent variable can explain the dependent variable, the model is mis-specified.

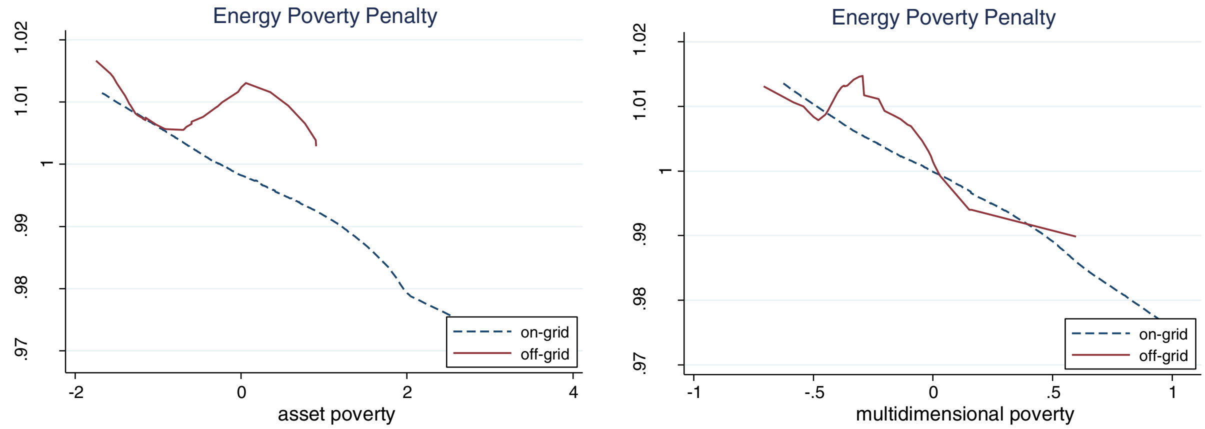

Fig. 4. Relative energy expenditure and poverty types.

expenditures and further bring down the significance of electricity. Higher education is negatively correlated with energy expenditure. It is assumed that higher education leads to higher asset income. In specification (4) controlling for the asset index based on multidimensional poverty, electricity becomes insignificant, which is intuitive since the new variable overlays its impact given that it forms part of the ratio of the dependent variable.

Therefore, an instrument is formed in order to control for income and to restrict its influence on the dependent variable in 2SLS regression model (III), shown in Table 11. Tables 4, 5 and 12 in Appendix C show the IV test and relevance/adequacy for the formed instrument, respectively. No collinearities can be detected.

As the instrument turns out to be insignificant and electricity shows significance at the 5% level, the first condition is further supported. It confirms that people spend on average more on energy if they do not have access to electricity with all other variables held constant. This, in turn, leads to the conclusion that if this analysis is correct, people also should spend more on energy in absolute terms at the same income level (see Table 14 below). The modifications show no sign of multicollinearity. The first specification still indicates OMV (when regressed on asset poverty), specification 2, though, does not suffer from OMV (see Table 13 in Appendix C) and is significant at the 5% level. Specification 3, again, shows relevance and adequacy for the formed instrument. No collinearities can be detected.

The results show significance for the asset index at the 1% and 5% level, respectively, in all modifications, stating the case that with higher

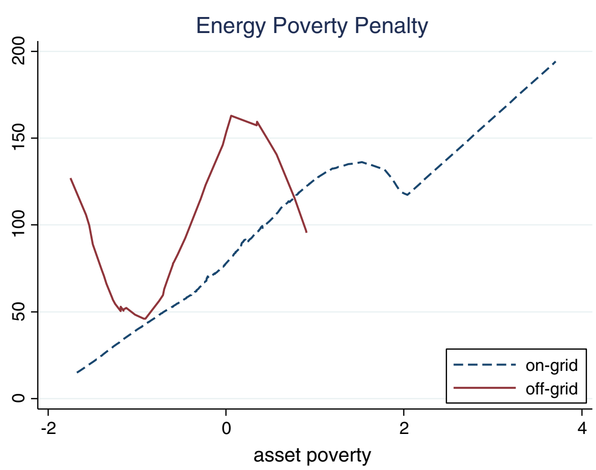

Fig. 5. Total energy expenditure and asset poverty.

Table 7
Determinants on relative energy expenditure.

Variables	(1)	(2)
	OLS	OLS
	Relative energy expenditure (multidimensional poverty)	Relative energy expenditure (asset poverty)
Credit	−0.00274*	−0.00300**
	(0.00157)	(0.00146)
Electricity	0.00112	−0.00416
	(0.00284)	(0.00567)
Micro-business	−0.00481***	−0.00206
	(0.00184)	(0.00160)
Distance	0.00171	0.00289*
	(0.00207)	(0.00168)
Two mobile providers	0.00225	0.00295
	(0.00234)	(0.00221)
One mobile provider	0.00190	0.00356
	(0.00247)	(0.00219)
No mobile coverage	0.00160	0.00534**
	(0.00258)	(0.00230)
Population density	2.10e−05	4.74e−05
	(9.36e−05)	(8.68e−05)
Electr. outage type	−0.000147	−0.000436
	(0.000929)	(0.000930)
Use of car batteries	0.00565	−0.00102
	(0.00414)	(0.00324)
Technol. adaptation	−0.000667	−0.000281
	(0.000544)	(0.000543)
Production potential	0.00143**	0.00140***
	(0.000568)	(0.000527)
Caylloma	0.00334	0.00333
	(0.00288)	(0.00275)
Castilla	−0.00247	−0.00476*
	(0.00282)	(0.00261)
La Unión	−0.00104	0.00333
	(0.00374)	(0.00288)
Arequipa	−0.000731	−0.000341
	(0.00717)	(0.00676)
Constant	0.995***	0.994***
	(0.00630)	(0.00769)
Observations	194	219
R-squared	0.101	0.162

Robust standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

Table 9
Determinants on relative energy expenditure (continued).

Variables	(1)	(2)	(3)	(4)
	OLS3	OLS3	OLS3	OLS3
	Relative energy expenditure (multidim. poverty)	Relative energy expenditure (asset poverty)	Relative energy expenditure (asset poverty)	Relative energy expenditure (multidim. poverty)
Credit	−0.00313**	−0.00267**	−0.00108	0.000369
	(0.00142)	(0.00136)	(0.00148)	(0.00130)
Electricity	−0.00769***	−0.00611**	−0.00537*	−0.00324
	(0.00264)	(0.00250)	(0.00310)	(0.00255)
Micro-business	−0.000963	0.00103	0.00119	0.00142
	(0.00125)	(0.00118)	(0.00122)	(0.00105)
Two mobile providers	0.00141	0.000585	0.00151	0.000188
	(0.00168)	(0.00156)	(0.00167)	(0.00145)
One mobile provider	0.00444**	0.00321*	0.00339*	0.00154
	(0.00189)	(0.00189)	(0.00189)	(0.00171)
No mobile provider	0.00284	0.00428**	0.00492**	0.00193
	(0.00203)	(0.00188)	(0.00199)	(0.00189)
Education			−0.000699**	
			(0.000314)	
Bathroom type			−0.00481***	
			(0.00155)	
Crowding			−0.00255**	
			(0.00125)	
Bathroom location			0.00436***	
			(0.00162)	
Cooking source			−0.00147	
			(0.000894)	
Multi. poverty				−0.0157***
				(0.00187)
Constant	1.006***	1.003***	1.011***	1.001***
	(0.00291)	(0.00278)	(0.00673)	(0.00273)
Observations	269	300	273	269
R-squared	0.107	0.100	0.169	0.285

Robust standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

income more money is spent for energy. Electricity is significant at the 10% level. Reapplying the instrument in specification (3) illustrates a significant impact of the IV-variable (income effect) but also shows significant results for electricity at the 5% significance level (energy poverty penalty). This implies that the income effect no longer overlays the EPP effect and proves the point that people spend more on energy in

Table 11
Model V regression on determinants on relative energy expenditure.

Variables	2SLS
	Relative energy expenditure (asset poverty)
Non asset poverty	−0.000234
	(0.00373)
Credit	−0.00272
	(0.00242)
Electricity	−0.00746**
	(0.00380)
Micro-business	0.00114*
	(0.00129)
Distance	0.000859
	(0.00108)
Constant	1.006***
	(0.00404)
Observations	281
R-squared	0.086

Robust standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

Table 14
Determinants on total energy expenditure.

Variables	(1)	(2)	(3)
	OLS3	OLS3	2SLS
	Total energy expenditure	Total energy expenditure	Total energy expenditure
Asset poverty	36.51***		129.1**
	(6.642)		(50.68)
Electricity	−42.89*	−43.92*	−76.89**
	(23.34)	(25.46)	(37.49)
Credit	4.587	4.030	−27.16
	(11.49)	(13.00)	(25.08)
Distance	−5.207	−8.628	15.74
	(8.000)	(8.778)	(13.74)
Microbusiness	15.12	11.14	4.509
	(9.299)	(10.28)	(14.30)
Education	−0.440	−0.213	−7.742
	(2.626)	(2.853)	(6.105)
Cooking source	−16.40**	−14.77*	
	(7.727)	(8.819)	
Bath type	−36.77***	−24.12*	−30.89**
	(11.81)	(13.81)	(14.08)
Multidim. poverty		81.11***	
		(18.64)	
Constant	228.3***	207.4***	229.2***
	(52.35)	(59.60)	(61.28)
Observations	275	247	265
R-squared	0.195	0.173	−0.274

Robust standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

Table 15
Determinants on energy poverty by different income classes.

Variables	Lowest income class	2nd lowest	3rd lowest
	Total energy expenditure	Total energy expenditure	Total energy expenditure
Multidim. poverty	−1.175	88.77	−24.31
	(63.39)	(67.90)	(97.06)
Education	−0.564	2.671	−5.290
	(5.474)	(4.291)	(8.033)
Crowding	−26.00	−2.951	−1.038
	(19.60)	(12.01)	(16.81)
Cooking source	−38.23**	−5.225	−13.90
	(16.56)	(9.280)	(18.72)
Bathroom type	−2.649	−8.870	−44.34
	(24.88)	(16.91)	(33.08)
Credit	3.368	−2.746	16.65
	(22.40)	(16.86)	(32.85)
Electricity	−68.21***	−56.12**	46.19*
	(24.42)	(23.12)	(97.86)
Constant	242.8**	149.4***	218.3
	(93.39)	(56.18)	(131.0)
Observations	71	111	74
R-squared	0.152	0.080	0.044

Standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

absolute terms given the same level of income measured through an asset index. Consequently, the second condition (regression model (V)) is met as well.

Regressing over more homogenous sub-panels by clustering over income classes (regression model (V)) reveals that clear evidence for the EPP is found only in the poorest income class when regressing on total energy consumption. In this case no instrument is used and income turns out to be a significant factor in both specifications. Since the income effect in the lowest income class is not as prevalent as in higher income classes, electricity remains significant at the 1% level in this lowest segment and at 5% in the second lowest, respectively.

No signs of heteroscedasticity can be found based on the Breusch–Pagan/Cook–Weisberg test.[30] Further the Ramsey RESET test does not detect an OMV for the first specification at the 1% level, and for the third specification on the 5% level. For the second specification the hypothesis that there is an OMV cannot be rejected. Calculating the variance inflation factor for each independent variable indicates no issues of multicollinearity (see Table 16 in Appendix C). Table 15 further indicates that the EPP seems to be most prevalent in the lowest income classes.

The paper's central result is a statistically significant evidence for the existence of the energy poverty penalty (EPP) while controlling for income and infrastructural poverty/structural handicaps. People living off the grid spend more money on energy relative to their total income and also in absolute terms given the same income level measured with an asset index. Moreover it is found that a proxy for income that takes into consideration more than personal assets but also basic infrastructure access can overlay this effect. We draw the conclusion from this observation that being remote implies a multitude of structural handicaps that can aggravate a poverty situation. Further disaggregation reveals that the EPP is most prevalent in the lowest income classes. The EPP concept enhances the understanding of the role that energy plays for people in remote areas living in poverty as it puts a challenge for their development by putting higher cost burdens on them.

In order to come up with empirical evidence for the developed concept of the EPP, the paper conducts a rigorous analysis of the energy uses, expenditures and income as well as infrastructural situation of 342 households and micro-businesses. Among the paper's key strengths is its detailed data collection, but also the stepwise approach of regression analysis that controls for structural handicaps and disaggregates the income effect from the energy penalty effect. It also shows that without these measures results are no longer robust. This distinguishes this paper from previous research on related issues where higher expenditures for energy poor people are demonstrated. Further, the often overlooked overlap in literature between electricity access and biomass dependency is estimated at 100%. The mobile phone coverage proxy used herein is a distinctive contribution in regression analysis on energy poverty, and reflects the criterion of remoteness to a better degree than measuring mere distance to the next capital city. The proxy gives insights on what constitutes energy poverty and supports the rationale of an energy poverty trap.

On a note of caution, the analysis exhibits comparatively low values of R^2. This is presumably due to the fact of low sample size but also because the data collection process still needs to be improved in order to obtain a higher quality data set. This can be attributed to questionnaire design, interviewers and sample size. Furthermore, three severe outliers among the residuals are detected, which indicate a violation of the normality assumption. Still, running some basic robustness tests show that the null hypothesis of the Ramsey RESET test (that there are no omitted variables) cannot be rejected indicating robustness for all model modifications. The author is also aware that the sample size for the strictly off-grid sector is very small ($n = 63$), leading to data sensitivity. Small business enterprises are ignored completely in the analysis so far.[31] The asset indices are only constructed as a mixed index, not distinguishing between households and micro-businesses. A further disaggregation might very well reveal more insights on the different impacts in terns of the magnitude energy poverty has on households and micro-businesses. High data quality remains a difficult task in these settings. Especially with respect to expenditure data, which are crucial to this analysis, measurement errors cannot be excluded (e.g. multiple use patterns, intangibility of energy, local research team dependency). Data do not tend to be distributed normally, and furthermore, non-linear relationships are not taken into consideration.

Conclusion

This paper forms part of the promising view to give the right players effective tools so that they can play a major role in combating energy poverty. It aims to shed light on the relationship between energy poverty, remoteness and implications for the people's development opportunities to help policy makers, planners and implementers in the studied country to better target their efforts. The paper presents statistically significant evidence for the existence of the Energy Poverty Penalty (EPP) while controlling for income and infrastructural poverty/structural handicaps. Both conditions (relative and absolute expenditure) for the EPP are met based on descriptive and empirical analysis of a dataset of 342 households and micro-businesses in rural Arequipa (Peru) using mobile phone coverage as a proxy for remoteness. It further indicates that living in a remote area implies a multitude of these structural handicaps leading to the conclusion that the existence of the EPP implies an

[30] It tests whether the estimated variance of the residuals from a regression are dependent on the values of the independent variables (Breusch and Pagan, 1979).

[31] According to the used definition, "small enterprises" refers to enterprises with more than five employees representing another field of research beyond the scope of this paper.

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aggravation of the concerned people's poverty situation. This, in turn, leads to the assumption that a poverty trap might occur. This trap is likely to inhibit – at least temporarily – the individual development path of the affected group members. Although further research is needed here, the paper presents some initial empirical evidence for oft-stated claims that the MDGs will not be reached unless energy inclusion measures targeting better energy service quality are taken. The existence of the EPP takes a first stand in favor of a uni-directional (or at least bi-directional) causality running from energy service quality to economic development (measured over income) leading to the claim that the role of energy is fundamental in the development process of low-income groups. In the bi-directional case it is an interesting field for future research to identify (a) possible turning point(s). Policy action could then be better targeted. This is particularly interesting against the observations made that energy inclusion measures might "come at a cheap price" based on the strong HDI impact accompanied with small changes in energy consumption. Considering the decoupling effect observed in Peru based on its human and energy development index (for low levels), it is recommended that the focus on energy inclusion measures be intensified which – following the same logic – will eventually also lead to higher incomes in rural areas. In the first phase the lowest income segments should be targeted since analysis shows that the EPP is most prevalent there. As for the type of measures, we recommend not to merely rely on subsidies on energy technologies, but investments into infrastructure facilitating the delivery of those. The recommendation is based on two results of this paper. First, structural handicaps are among key factors leading to the EPP and therefore need improvement efforts. Second, energy use is diverse, and so is the use of energy technologies. By investing into better delivery channels a multitude of technologies can be channeled toward the energy poor. Having said that, this type of support directly targets the group most affected by the EPP, instead of benefiting all through a product subsidy with less impact. As small enterprises had to be ignored in the data collection, there is an interesting future field of research to distinguish energy demand between micro-businesses, mixes of household/micro-businesses and small enterprises. There is indicative evidence found that mobile phone coverage serves as a better proxy for remoteness than mere distance measures. The analysis further reveals that there are strong in-country differences and that general statistical data is not always reliable, making the interpretation of composite indices difficult beyond the level of benchmarking performance between countries.

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Appendix A. Questionnaires

Appendix A1. Village profile (translated to English)

APPENDIXES

A Questionnaires

A1 Village profile (translated to english)

Interviewer: ________________ Date: ________________

LOCAL MARKET RESEARCH QUESTIONAIRE

Province: ______________________

Parish: ______________________

Location: ______________________

GPS signals: ______________________

Do you have a connection to the electricity grid? Yes No

If not, what is the distance to the grid: _____ km _____ time on foot / by car

Do you have mobile coverage? Yes No Movistar Caro Nextel

If not, what is the distance to the next coverage point: ______ km _____ time on foot / by car

Price of electricity per kWh: Residential Area: ________ Commercial Area: _______

Blackouts: _______ per day: _______ per week: _______ per month: _______

Seasonal Differences ____

Other sources of energy: ____

Business energy sources: ____

Description of the area: ____

____

____

Main economic activity in the area:

____

____

____

Are MFIs present: Yes No

Which: ____

Product	Nearest dealer	Distance to the dealer	Transport costs (S /.) ROUND TRIP private / public	Sale price (S/.)
LPG (gas)		____km ____min		
Kerosene/Petrol		____km ____min		
Candles		____km ____min		
Parrafin		____km ____min		
Firewood		____km ____min		
Batteries		____km ____min		
Car Batteries		____km ____min		
Light bulbs		____km ____min		
Combustible generator		____km ____min		
Cost of recharging car battery		____km ____min		
Cost of recharging mobile phone battery		____km ____min		
Biogas plant		____km ____min		
Solar panels		____km ____min		
Other		____km ____min		

Technology penetration

Other commonly used applications or technologies available for sale: ____________________

Are there people with solar panels? Yes No In the urban area of the village On the farms

Are there people with biogas plants? Yes No In the urban area village On the farms

Are there repair services available for this kind of equipment? If yes, then where?

____

Cultural norms: ____

____

Other comments:

____

____

____

Appendix A2. Household/micro-business survey (translated into English)

A2 Household/ micro-business survey (translated into English)

Questionnaire for the area of Arequipa: Energy Expenditures

Household/ micro-business code: **Interviewer:** **Date:**

Introduction (Read to the interviewee and show your identity card)

Good morning, my name is______________________
We are interested in your opinion for a university study on the energy situation in the area. All information provided by you will be treated with the strictest confidentiality. Regarding the questions, there are no right or wrong answers. Today's interview will last approx. 10 minutes. Know that the information you give me will help me to conduct the study.

We can then begin the interview? Yes O No O

General characteristics

1. How many people live in your household? (including you) _________________
2. How many people under 5 years live in your household? _________________
3. How many rooms does your house have? _________________
4. How many windows does your house have? _________________
5. Where does your drinking water come from?
   o pipe o surface o well o bought in bottles o other ________
6. Your bathroom is…
   o inside o outside o with drainage o without drainage
7. Which of the following appliances or things do you have??
   o Radio o Sewing machine o Car
   o TV o Hot water o Bicycle
   o DVD o Refrigerator o Motorcycle
8. How are you cooking?
   o with electricity o or sometimes with _________ and with ______________
   o with gas o mostly with ____________________________________
   o with wood o other ____
9. What is the highest level of education of the head of the household or micro-business?
   o no formal education o higher education, not uni, completed
   o primary school incomplete o uni incomplete
   o primary school completed o uni completed
   o secondary school incomplete o postgraduate
   o secondary school completed o other ___________________________
   o higher education, not uni, incomplete o does not know

10. Do you have a credit or savings account at a financial institution?
    o Yes o No o don't know
    If not, then why not?
    o there are none nearby o do not qualify o other _______________________
11. Animals

	Cows	Cattle	Chickens	Guinea pigs	Horses/ Donkeys	Camelidos Llamas	Pigs	…
Number								

12. Do you sell anything from home ? o Yes -> **13** o No -> **14** o don't know -> **14**
13. What is the best description of your business?
    o restaurant o trade and sales o agriculture o don't know
    o accomodation o other ___________________________________
14. Do you have farmland? o Yes How much? _______hectares o No

Energy expenditure

15. Is your home connected to the electricity grid o Yes -> **16** o No -> **21**
16. Does your home have an electricity meter?
    1 o Yes -> **request bills for the past three months and note the amounts**
    2 o No -> **request a cost estimate**
    month 1: S/ month 2: S/ month 3: S/
    lowest price S/_______ price per kWh S/_______
17. How many times per day do you have blackouts, and how long do they last?
    ____times ____hours o don't know
18. What form do the blackouts take?
    o unplanned and unannounced o both forms, but more unplanned
    o planned and announced beforehand o both forms, but more planned
    o other ____________________ o don't know
19. Normally how many days per week do you NOT have electricity? [ ] o don't know
20. In what way do the blackouts affect your home or your business?
    o severely o slightly o don't know
    o strongly o not affected o other________________________
    o somewhat

21. Why do you not have access to the electricity grid?

Reason	Not applicable	Partly applicable	Applicable
There is no electricity in this area	o	o	o
We cannot pay the costs of connection	o	o	o
We cannot pay the ongoing monthly costs	o	o	o
We cannot pay for the electrical equipment	o	o	o
We do not need it	o	o	o

Other________________________________

The nearest village with lights is about ____km away.

22. What is used instead of electricity (during blackouts or if there is generally no electricity)?
    o candles o gas lamps o flashlights
    o kerosene lamps o car batteries o photovoltaic equipment
    o petromax o generator o other________________
23. How much do you spend on these things?

Resource (per month)	Unit	Price	# refills	Total cost	Time	Use *	*
o gas		S/		S/	h		**Cooking COC**
o wood		S/		S/	h		**Lighting LUZ**
o kerosene/diesel/petrol		S/		S/	h		**Heating CAL**
o car batteries		S/		S/	h		**Refrigerating/Freezing FRIO**
o batteries		S/		S/	h		**Radio, TV, DVD INFO**
o PV equipment		S/		S/	h		**Telephone, Internet COM**
o …		S/		S/	h		
o …		S/		S/	h		**Labour/Work** TR**

** specify ____

	N/A	Partly Applies	Applicable	Don't know
24. Are you having trouble finding firewood?	o	o	o	o
25. Have there been many rises in the price of firewood	o	o	o	o
26. Do there seem to be fewer trees now	o	o	o	o

27. What is the level of energy knowledge? 1 – 7 * [ ]
28. What is the capacity for production? 1 – 7 * [ ]
29. Are the energy technologies adapted to the end-user needs? 1 – 7 * [ ]

* 1 represents very low knowledge, 7 represents very high knowledge

THANK YOU FOR YOUR PARTICIPATION

Appendix B. Figures

Source: ArcGIS plotting with GPS data
The coordinates in the indicated crème colored box belong to the capital Arequipa.

Fig. 1. Research village with respective GPS coordinates. Source: ArcGIS plotting with GPS data. The coordinates in the indicated cream colored box belong to the capital Arequipa.

Appendix C. Tables

Table 1
Data sample on the provincial level in comparison to official statistics.

Province	Capital	Sample	Sample %	Pop. total	Pop. %
Arequipa[a]	Arequipa	87	25.44	155,555	34.11
Camaná	Camana	0	0.00	55,483	12.17
Caraveli	Caraveli	19	5.56	37,796	8.29
Castilla	Aplao	63	18.42	39,317	8.62
Caylloma	Chivay	113	33.04	79,485	17.43
Condesuyos	Chuquimbamba	18	5.26	19,169	4.20
Islay	Mollenudo	24	7.02	53,471	11.73
La Union	Cotahuasi	18	5.26	15,750	3.45
Total[a]		**342**	**100.00**	**456,026**	**100**

[a] Population of Arequipa city was subtracted.

Table 2
Asset index variables.
Source: Structure taken from Moser and Felton (2007).

Type of capital	Category	Variable
Physical	Infrastructural living conditions	Drinking water source
		Cooking source
		Toilet type
		Toilet location
	Housing durables	Hot water
		No. of rooms
		No. of windows
		Crowding (available rooms/no. of people)
	Consumer durables	TV
		Radio
		DVD
		Bicycle
		Motorbike
		Car
		Fridge
Productive	Productive durables	Agricultural land
		Sewing machine
		Animals (pig, guinea pig[a], camelid, horse, donkey, chicken, bovines)
Human	Education	Level of education of household head

[a] Guinea pigs are not considered as pets in Peru but as a delicacy, so there are a lot of small breeding businesses existing.

Table 3
Income class clusters and difference test in means.

Variable	Obs	Mean	Std. dev.	Min	Max
– Income class 1					
Multi. asset index	123	0.030	0.118	−0.199	0.232
– Income class 2					
Multi. asset index	83	0.447	0.172	0.241	0.901
– Income class 3					
Multi. asset index	95	−0.430	0.145	−0.745	−0.202

Test for equality of 3 group means

	Statistic	Prob. >F
Wilks' lambda	0.1514	0.0000 e
Pillai's trace	0.8486	0.0000 e
Lawley–Hotelling trace	5.6064	0.0000 e
Roy's largest root	5.6064	0.0000 e

Table 4
Instrumental variable test: correlation analysis with dependent variable.

Variables	(1)
	OLS3
	Relative energy expenditure
Education	−0.000972***
	(0.000363)
Crowding	−0.00241**
	(0.000977)
Bathroom type	−0.00452***
	(0.00150)
Source for drinking water	**−4.52e–05**
	(0.000304)
Location of the bathroom	0.00492***
	(0.00164)
Type of cooking source	**−0.000517**
	(0.000870)
Constant	1.006***
	(0.00475)
Observations	273
R-squared	0.104

Standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

Table 5
Instrumental variable test: correlation analysis with multidimensional poverty.

Variables	(1)
	OLS3
	Asset index
Type of cooking source	**−0.0605*** **
	(0.0216)
Source for drinking water	**0.0153** **
	(0.00756)
Education	0.0426***
	(0.00892)
Crowding	0.0679***
	(0.0235)
Type of bathroom	−0.203***
	(0.0367)
Location of the bathroom	−0.310***
	(0.0397)
Constant	0.755***
	(0.116)*
Observations	260
R-squared	0.503

Standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

Table 8
Robustness test for model 1.

Test	Specification 1: On multidim. poverty	Specification 2: On asset. poverty
Ramsey RESET test	F(3, 174) = 0.90	F(3, 199) = 0.64
Ho: model has no omitted variables	Prob > F = 0.4447	Prob > F = 0.5871
Variance inflation factors		
Thumb rules applied:	Mean VIF = 3.09	Mean VIF = 3.09
1. The largest VIF is > 10	Population	Population
2. The mean of all the VIFs is > > 1	density = 13.08	density = 12.97

Table 10
Robustness test for modified model I.

Test	(1)	(2)	(3)	(4)
Ramsey RESET test	F(3, 259) = 0.11	F(3, 290) = 1.25	F(3, 258) = 2.00	F(3, 258) = 1.78
Ho: model has no omitted variables	Prob > F = 0.9567	Prob > F = 0.2930	Prob > F = 0.1148	Prob > F = 0.1513
Variance inflation factors				
Thumb rules applied:				
1. The largest VIF is > 10	Mean VIF = 1.36	Mean VIF = 1.39	Mean VIF = 1.36	Mean VIF = 1.41
2. The mean of all the VIFs is > > 1				

Table 12
Robustness test for model IV.

Test	2SLS estimation
Anderson- LR statistic	16.811
Ho: model IV relevance	$\chi^2(2)$ P-val = 0.0002
Hansen J statistic	0.088
Ho: over identification test of all instruments	$\chi^2(1)$ P-val = 0.7663

Table 13
Robustness tests for model V.

Test	Specification 1: On asset poverty	Specification 2: On multidim. poverty	Specification 3: with IV
Ramsey RESET test	F(3, 263) = 1.68	F(3, 235) = 2.81	–
Ho: model has no omitted variables	Prob > F = 0.1710	Prob > F = 0.0399	
Variance inflation factors			
Thumb rules applied:			
1. The largest VIF is > 10	Mean VIF = 1.19	Mean VIF = 1.26	–
2. The mean of all the VIFs > > 1			
Anderson-LR statistic			9.059
Ho: IV relevance	–	–	$\chi^2(2)$ P-val = 0.0108
Hansen J statistic			0.633
Ho: over identification test of all instruments):	–	–	$\chi^2(1)$ P-val = 0.4263

Table 16
Robustness test for model V.

Test	Lowest income class	2nd lowest	3rd lowest
Breusch–Pagan/Cook–Weisberg test for heteroskedasticity	$\chi^2(1) = 84.71$	$\chi^2(1) = 24.47$	$\chi^2(1) = 7.45$
Ho: constant variance	Prob > $\chi^2 = 0.000$	Prob > $\chi^2 = 0.000$	Prob > $\chi^2 = 0.0064$
Ramsey RESET test	F(3, 60) = 7.68	F(3, 100) = 3.41	F(3, 63) = 1.30
Ho: model has no omitted variables	Prob > F = 0.0002	Prob > F = 0.0204	Prob > F = 0.2837
Variance inflation factors			
Thumb rules applied:			
1. The largest VIF is > 10	Mean VIF = 1.25	Mean VIF = 1.12	Mean VIF = 1.20
2. The mean of all the VIFs > > 1			

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Chapter 3

Off-grid rural area electrification through solar-diesel hybrid minigrids in Bangladesh: resource-efficient design principles in practice

"Scientific and technological "solutions" which poison the environment or degrade the social structure and man himself are of no benefit, no matter how brilliantly conceived or how great their superficial attraction."

- E.F. Schumacher,
1973

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Off-grid rural area electrification through solar-diesel hybrid minigrids in Bangladesh: resource-efficient design principles in practice

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ABSTRACT

With around 40% of the population without access to electricity but also a high penetration of solar home systems in its off grid areas, the case of Bangladesh is a very strong reference for the applicability of the Sustainable Energy Access for All (SE4A) goals. Nonetheless, while the solar home system program with 3.6 million systems has gained worldwide recognition, there are considerable limitations in the usage of such systems, in particular in the ability to provide access to higher tier energy services for productive use. Minigrids, on the other hand, could provide this access but have yet to proof both scale and commercial viability. This paper provides critical insides into the case of Bangladesh for a cost-effective route to the SE4All goals by applying practical and resource-efficient minigrid design principles. Planning and operation techniques are elaborated on in detail and concluded with a financial analysis for a hybrid solar-PV-Diesel minigrid that provides enhanced energy access in particular for productive use. In addition, implications on the business model are highlighted for developing minigrids in off grid rural areas of Bangladesh for hybrid minigrids ranging from 100 to 250 kWp while exemplarily showing how the three goals of the United Nation Sustainable Energy for All Initiative can be pursued in a mutually beneficial way.

1. Introduction

The Sustainable Energy Access for All (SE4A) goals have a large application ground in Bangladesh: 40% of population, approx. 65 million people, are without access to electricity (World Bank, 2013). Hence, more than 8% of the 800 million people in Asia with inadequate access to electricity live in the country (Intellecap, 2012). For the grid-based electricity access, the government plans an increase in renewable energy share to 5% of the total power generation (~500 MW) from renewable sources by 2015 and 10% (~2000 MW) by 2020 (GoB, 2008). The off-grid sector in the country has gained world-wide recognition for its solar home system (SHS) based rural electrification program that has installed approximately 140 MWp throughout the country (IDCOL, 2014). These small electricity access systems currently consist of a 20 to 100 Wp solar panel, a lead acid battery, a charge controller and basic loads. Under the Infrastructure Development Company Limited's (IDCOL) national SHS program, up to 75,000 system are being installed every month, currently amounting to 3.6 million systems in total as of today (IDCOL, 2015). Regardless of this success, there are certain limitations of this electrification option. A key concern, in particular in regard to the SE4Aall goals is the inability to reach down to the poorest demographic segment (Samad et al., 2013). Also, in regard to the ability to utilize the energy access for productive use, there are clear restrictions (Rahman et al., 2013a). On the other hand, the systems are generally over-sized to assure high reliability, which in turn leads to excess capacity. Excess capacity is the generated energy that gets lost as the battery is full. The systems are embedded into a single household, leading to a lack of flexibility in terms of usage patterns and payment methods (Chakrabarty et al., 2011). Based on the logistical constraints and geographical challenges

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USE OF ELECTRICITY SERVICES

TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
-	Task lighting **AND** phone charging (OR radio)	General lighting **AND** television **AND** fan (if needed)	Tier 2 **AND** any low-power appliances	Tier 3 **AND** any medium-power appliances	Tier 4 **AND** any high-power appliances

Fig. 1. Multi-tier framework for energy access (Source: UN, 2014).

seen in developing countries in respect of the access to energy, approaches aimed at developing electrification in rural areas can help to increase life quality on the one hand, and help economic growth on the other. This is because access to energy can also assist in the development of business activities where heating or cooling are needed, creating opportunities to raise income, and hence help to reduce what the authors regard as "energy poverty", i.e. poverty due to lack of access to energy. As shown in recent publications, this paper joins the effort to distance itself from a binary category of energy access towards a multi-tier framework in order to be able to measure a continuum of improvement (UN, 2014b; Muench and Aidun, 2014; Groh et al., 2014). The quality of electricity supply through the main grid varies substantially (e.g. in terms of black- & brown-outs, voltage fluctuation, among others) in different countries, regions of a country[1] and even parts of the same city. The quality of decentralized energy system varies even more in terms of possible loads to connect (electricity services), time and duration of usage. Furthermore, a measurement in Wh per household counteracts a strive for more energy efficient appliance run with those systems. These multiple access solutions, partly designed as transitional solutions or even running in parallel, need to be assessed reflecting these differences in service supply. Therefore, reference is taken here to the multi-tier approach to measuring energy access, distinguishing five tiers based on six attributes of electricity supply as briefly depicted in Fig. 1.[2] SHS with the currently applied sizing can usually only provide for tier 1 and 2 energy access.

To allow the off-grid population in Bangladesh to develop further economically, socially, but also technologically, the way forward into different tiers needs to be explored. One heavily discussed option could be the intensified application of minigrids. Such small scale projects will provide electricity to rural people and can contribute significantly to improve their quality of life (Khan and Huque, 2014). At the same time, these projects, when designed properly, can be sustainable and economically viable and thereby comply with the three set target of the UN Sustainable Energy for All Initiative (SE4A), namely "to ensure universal access to modern energy services (including electricity and clean, modern cooking solutions), to double the global rate of improvement in energy efficiency, and to double the share of renewable energy in the global energy mix by 2030" (Ki-moon, 2011). Against this background, minigrids have been identified as a high impact opportunity by the SE4ALL committee (UN, 2014a). This paper indicates how improved energy efficiency results in lower energy prices which in turn increase affordability leading to a higher degree of energy inclusion (Groh, 2014). It further emphasises on the possibility that higher share of solar resources open up new possibilities for providing electricity to the most remote and dispersed populations (UN, 2014; Léna, 2013), keeping in mind a project design that refrains from being technology driven and aims for all key stake holders - consumers, service and technology providers, financiers, and government — to benefit (Terrado et al., 2008). Even if the grid is extended in the future to the stand alone minigrid areas, the solar PV can be connected to grid by the grid tied inverters. Nonetheless, there is a paucity of publications which explore the potential contributions of minigrids and their potential contribution with respect to resource efficiency, renewable energy share and increased energy access which is addressed herein.

2. Local functional project structure

Sustainable rural electrification based on hybrid systems heavily relies on the impetus given by institutions that oversee the provision of rural public services (Léna, 2013). As high upfront cost is a critical obstacle in the scale up of clean infrastructures in the Global South (Huenteler et al., 2015; Liew et al., 2014), among other factors such as quality assurance and the build-up of a local industry (Samad et al., 2013), a concerted effort resulting in the uptake of the renewable energy program through the Infrastructure Development Company Limited (IDCOL) has been pursued. IDCOL is a non-bank financial institution, established by the Government of Bangladesh in 1997 with a focus on public private partnerships and such nursing the development of an entire local renewable energy industry with significant learning effects (IDCOL, 2014). The important of this approach can be underlined referring to research by Huenteler et al. (2015) stating that "conditions enabling local learning […] have a more significant impact on cost of renewable energy in developing countries than global technology learning curves" (Huenteler et al., 2015, pp. 1). The blend of international support through a national institution relying on strong links with the local sector and high quality focus so far has proven to be a viable approach in Bangladesh in contrast to experiences in other areas in the world.[3] The solar-diesel hybrid minigrid system for rural electrification program in Bangladesh is supported by IDCOL since 2009. The program is financed by the international donor community which provides soft loans and grants to IDCOL which in turn channels the soft loans and grants to the developers of solar minigrid projects. Project developers are encouraged to submit proposals for the financing of solar hybrid minigrid projects to IDCOL. These developers choose a remote off-grid area which has the potential for the installation of a minigrid. They also appoint consultants for design and developing the project profile for IDCOL

[1] In Bangladesh for instance the grid for the rural areas is run by a different institution than for the urban area, namely the Rural Electrification Board.

[2] For further reference please refer to the Global Tracking Framework by UN 2014.

[3] Please refer to Reiche et al. (2002) for a general overview, for analysis on Argentina to Alazraki & Haselip (2007), for Peru to Cherni and Preston (2007), and for Cameroon to Pineau (2007).

financial support. Based on the market survey conducted by the project developers, IDCOL, in consultation with the sponsor and the consultant, conducts load assessments. The technical consultant then designs the hybrid system and prepares a bill of materials for the project and also supports developers to select suppliers based on the bill of material for the project. After arriving at the project costs based on submitted price quotations, IDCOL approves the project and starts the documentation process for financing the project.

The financial scheme for the solar-diesel hybrid minigrid project developed by IDCOL is 50% grant, 30% soft loan (interest rate 6%) and 20% equity from the project developer. The soft loan is given for a tenure of ten years with a two year grace period. Under this financial scheme, one project was successfully installed in Sandwip island in the estuary of the Bay of Bengal in 2010. Initially, the project aimed to provide electricity to a rural market and its adjacent households from 9 am in the morning to 11 pm at night. IDCOL further approved 3 more solar minigrid projects which came into operation at the end of 2014. Seven other projects have already been submitted to IDCOL for financing considering uninterrupted power supply for 24 h. IDCOL has a target of installing 50 solar-diesel hybrid minigrids all over Bangladesh by 2016 (IDCOL, 2014). Léna (2013) argues that a clear organizational scheme in combination with capacity building and access to concessional financing are key enablers for the development of this segment.

3. Key design principles

In order to yield maximum benefits in terms of the SE4A goals until 2030, critical design principles must be applied to the actual scenario of the project location for minimizing the cost of energy and increasing sustainability through resource efficiency. The general design steps of the solar-diesel hybrid minigrids are shown in Fig. 2 and follow the principles of grassroots innovation putting “local knowledge and communities in the lead in the framing of a collaborative innovation activity” (Smith et al., 2014, p. 114). It further ensures that socio-cultural dimension is not neglected as the non-compliance with societal issues turns out to be among the key reasons of failure in the past (Rahman et al., 2013).

Whereas the site survey explores the feasibility of the minigrid, the demand assessment feeds into both, the technical and financial design and used be explored in parallel allowing for mutual adjustments. The site survey is the initial step in the planning process in order to find an adequate location. Survey findings are helpful since they show the feasibility of a project in the present and future context. Parameters for survey vary from one location to another. At first, ability and willingness to pay of the end-users need to be addressed. Secondly, remote and isolated locations are ideal for minigrid sites such as islands and habitations that are far away from the national grid network. The sites are selected on the basis that they will not receive national grid connection in the next ten years. As for IDCOL requirements, the levelized tariff of electricity stands

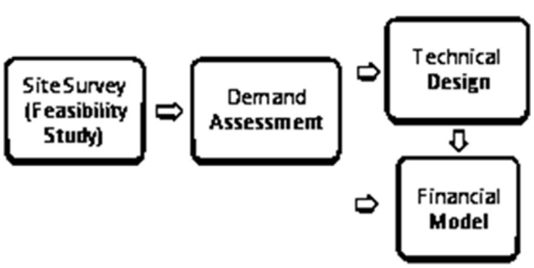

Fig. 2. Design steps for solar-diesel hybrid minigrids.

Table 1
Typical loads for different packages.

High impact area for distributed electricity solutions (UN 2012)	Respective design principles
Address consumer needs (B2)	1. Survey-based load estimation 2. Estimation of day load and night load with their respective variations 3. Estimation of seasonal load variation
Support productive use (B2)	1. Allow for the usage of appliance up to tier 5 (UN 2014) and above 2. Identify potential day loads for productive activities 3. Lights support evening markets
Support local business creation (B2)	1. Battery performance is engineered for small lifespan costs 2. No autonomy for designing battery size, reducing storage costs 3. Marketing of energy efficient appliances is supported
Develop smart grid solutions (B4)	1. Diesel generator is for mainly used as backup power and battery equalizing charging 2. Sizing of diesel generator considering peak load and hours of operation. 3. Demand response: incentivise day loads
Minimum performance standards (B4)	1. Solar resource assessment and PV array sizing on the basis of hourly irradiation data 2. Length of distribution feeders considering an average 5% voltage drop at the end of distribution line. 3. Governmental approval for PV generation capacity >250 kW (GoB 2013).

at US$ 0.37 for a typical 141 kWp hybrid system this is much higher than the energy tariff (US$ 0.11) of grid electricity (GoB, 2012).

The average family income and profession of the adults of the location reflect the interest and affordability of electricity. Site surveys show that there are some areas where people cannot afford to buy electricity, on the other hand, some off-grid places are found to be economically developed and people are willing to pay a high price for electricity round the year (Khan and Huque, 2014). People use kerosene with adverse health effects (Ahmad and Puppim de Oliveira, 2015) to meet their lighting demand in some off grid areas while in other off-grid areas, diesel generators are also used to provide electricity for some hours per day. Mini-utilities based on diesel generators supply neighbouring houses as well as small businesses to a tier 1° and in a few cases a tier 2°.

Finally, a load assessment is the most indispensable tool to determine the size of the power plant. In the context of rural Bangladesh, lighting, cooling fans and mobile phone chargers are the main loads. TVs, refrigerators and DVD players are also found to be potential loads. Rural sites for minigrids are selected to cover one or two rural villages with a rural market place. This paper gives a detailed case study for the case of Bangladesh, how SE4Aall targets can be implemented in a practical manner. In the SE4All global action agenda, particular high impact areas have been identified for distributed electricity solutions, including minigrids (UN 2012). The foundation for energy efficient implementation are the design principles that are based on these high impact areas, as listed in Table 1. In the following section these are elaborated on in more detail stating concrete examples.

Hence, the design principles feed through a mutual supportive way into the SE4A goals:

3.1. Reliability of renewable energy sources for universal energy access

Different renewable energies technologies of minigrid power systems are available worldwide. A combination of technology

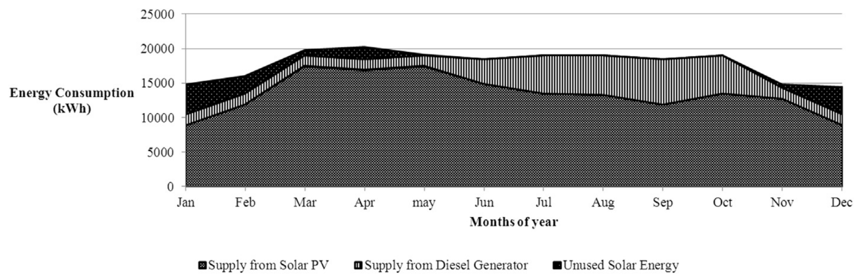

Fig. 3. Energy mix for a 141 kWp solar diesel hybrid minigrid in rural Bangladesh (the system is designed for electrification of 998 Households and 45 shops in an island of Padma river at Bagha of Rajshahi district).

sources provides higher chances to overcome certain technical challenges (Léna, 2013). Furthermore, with decreasing PV prizes, the portion of solar in hybrid schemes gains in viability. In Bangladesh, solar-diesel hybrid minigrids are considered to be the most suitable solution: the annual average solar radiation is around 5 kWh/m^2/day on the optimum tilt angle (the tropic of cancer passes though almost on the middle of Bangladesh and the optimum tilt angle for maximum solar radiation on a fixed tilt is considered 23.5°). Other suitable RE source for rural electrification can be biomass and wind or hydro energy (Mondal and Denich, 2010), but none of these other RE source have such a reliable potential as solar. Biomass is, due to its availability and cost considered to be the most popular energy source in the rural areas of Bangladesh, but is hardly utilized in the electricity generation sector. Though there were some initiatives but overall less successful. The first biomass gasification based power plant was installed in 2008 in Giaspur, Kapasia of Gazipur district, the capacity of power plant was 250 kW, but the operator is not able to run power plant commercially. The average annual wind speed in Bangladesh (on shore) is less than 4 m/s, which is not suitable for wind turbine based rural electrification program.

3.2. Renewable energy fraction in the energy mix

A higher renewable energy fraction in the annual energy mix reduces the need for diesel fuel and hence operational expenditure for the energy supply system. Transportation of diesel oil to remote places is cumbersome. For the hybrid projects in Bangladesh the RE fraction is considered to be more than 90%. A higher renewable energy fraction also keeps options for future demand growth as the diesel generator will only be needed once demand has risen. The major energy-consuming load type in the rural areas of Bangladesh is cooling fans. During winter cooling demand is almost negligible. So, during the winter season, a large portion of the energy generated from the solar PV system is not utilized. Fig. 3 shows a simulated energy mix diagram of a minigrid of 141 kWp in an island of Padma river (Bagha, Rajshahi) area, designed for supply electricity to rural households and small business around a village market. The renewable energy fraction of this grid is 89% and the unused or excess energy from solar PV is 8%.

3.3. Energy efficient appliance usage

It is crucial to provide/make sure there is access to adequate electricity appliances that can be run with the infrastructure as electricity supply is only one part of the equation sustainable electricity service. Often people are left with very inefficient appliances leading to high consumption system capacity challenges which results higher capital expenditure, leading to higher end-user tariffs and absolute costs which severely weakens the affordability dimension.

3.4. Productive use of solar power

during daytime, productive or income generating activities such as solar irrigation, cottage industries, husking mills, sawmills, grinding mills (for spice), welding machines, lathe machines, and ice factories in rural market places can be supported through the solar minigrids. Because these loads are run during the day, when solar irradiation is highest, hardly any storage devices are needed. Therefore, cost of electricity for daytime loads is cheaper than the cost of electricity for night time loads. Fig. 4 shows the energy mix diagram of a designed solar diesel minigrid in the same district as above (c.f. Fig. 3). However, in this design 14 irrigation pumps were incorporated to utilize the excess energy from the solar PV hybrid minigrid. This approach then allows for a *smart*, demand response schedule, where pumps are used whenever supply from solar is abundant.

Fig. 4 shows the simulated energy mix diagram of a minigrid of 148.5 kWp in an island of Padma river (Godagari, Rajshahi) designed to supply electricity to rural households and small businesses around a village market. Additionally this minigrid provides power to 14 intelligently incorporated irrigation pumps. The irrigation pumps are allowed to draw power during the day only. The RE fraction for this minigrid is 94.55% and unused or waste of energy generated from solar PV is 2.6%.[4] Therefore, daytime loads should be encouraged while designing minigrids.

Fig. 5 below shows the energy requirement of 14 irrigation pumps per month. July to October is the rainy season for Bangladesh, so there is no need of irrigation demand during the rainy season. Solar radiation also reaches its minimum during that period.

3.5. The addition of a generator reduces battery requirement

A diesel generator can be used as a tool to reduce the size of the storage system for a minigrid. Therefore, no autonomy days need to be considered, but the storage system needs to be sized large enough to allow for a smart transition between diesel and solar energy. In particular, times when diesel generators would run at low relative power output need to be avoided as these are associated with high losses.

In conclusion, the design aims to minimize capital and operational expenditure through a smart integration of renewable and energy efficient technologies which in turn make the minigrid an attractive energy access option in terms of quality of electricity services combined with its affordability.

[4] The system (Fig. 5) is designed for electrification of 866 households, 116 shops in rural market, 10 primary schools and mosques and 14 irrigation pumps of 2 kW power rating. The system is designed for an Island of Padma river in Godagari Upazilla of Rajshahi district).

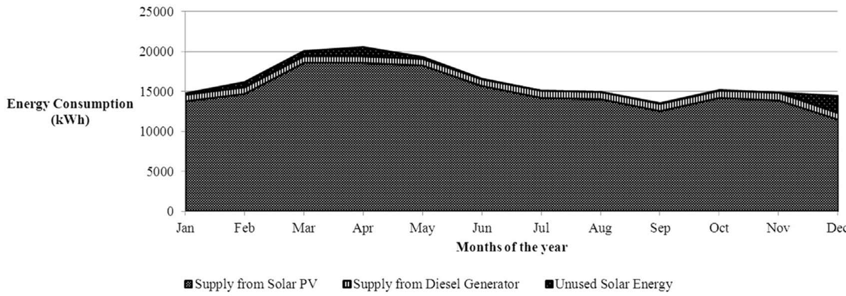

Fig. 4. Energy mix diagram of a 148.5 kWp solar diesel hybrid minigrid where productive day load (irrigation pumps) is added.

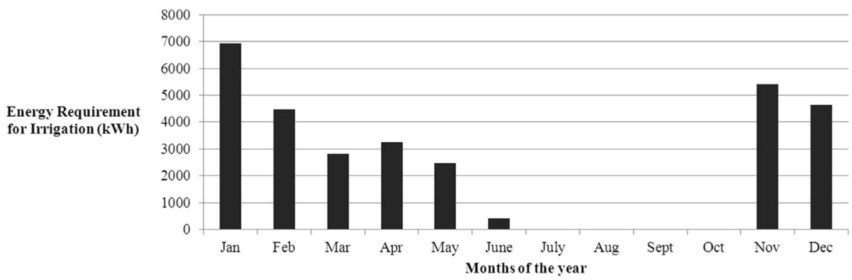

Fig. 5. Annual energy requirement of 14 irrigation pumps for the minigrid (148.5 kWp) of Godagari Unioon of Rajshahi district.

4. Demand assessment

Demand assessments in rural areas need to be performed with great care as rural people are not familiar with electrical loads other than lighting and cooling. Their expectations are influenced by those who live in or frequently visit urban or city areas. They want to use luxury loads like TVs, DVD players and refrigerators irrespective of the energy consumption. Very careful assessment should be in place to assess the rational load demand. Monthly income is often better measured by through the use of asset indices (number of rooms, consumer durables, etc.), all income generating activities need to be analysed to the degree where electricity plays a role and what is the respective expenditure for it (Groh, 2014).

Table 2
Typical loads for different packages.

Package	Appliance type	Watt	Quantity
Package 1 (Small Household)	LED light	7	3
	Cooling fan	25	1
Package 2 (Medium income Household)	LED light	7	4
	Cooling fan	25	2
	TV	50	1
Package 3 (Well off Household)	LED light	7	6
	Cooling fan	25	2
	TV	50	1
Package 4 (Rich Household)	LED light	7	6
	Cooling fan	25	3
	TV	50	1
	Refrigerator	100	1
Package 5 (Shops)	LED light	7	2
	Cooling fan	25	1
Package 6 (Big Shops)	LED light	7	4
	Ceiling fans	25	2
	TV	50	1
	Refrigerator	100	1
Package-7 (Rural School & College)	LED light	7	10
	Cooling fan	25	20
Package-8 Industrial (Saw mills, Lathe m/c, others)	LED light	7	1
	Cooling fan	25	1
	Motor	5000	1
Package 9 (Irrigation pumps)	Motor	2000	1

4.1. Packages

To overcome actual load assessment barrier, different packages should be defined for different types of users according to their income level. The packages should be designed using energy efficient loads, for example LED lamps, higher efficiency cooling fans etc. Furthermore, to settle the load as a package, a relation between monthly energy price and present monthly cost for energy should be analysed, so that the people can realize their expenses. Based on the survey findings in seven rural off grid areas, the consumer packages developed are shown in Table 2. It also shows the breakdown of each package according to the demand of rural households. The ratio of the packages varies with the variation of socio-economic condition of that locality.

4.2. Load factor

The rural economy of Bangladesh is mostly dependent on agriculture. Rural inhabitants work on their land all day long and go to sleep early in the evenings. However, the scenario may not remain the same after electrification; therefore, the load factor (the hours per day the appliances are used) needs to be estimated considering the predicted scenario after electrification. One example is that of cooling fans which are negligible during winter.

4.3. Daytime load

The cost of energy in a solar-diesel hybrid minigrid system is high compared to the national grid. Main reason behind this is the high price of the storage system and the cost of diesel. It is possible to reduce the energy cost to a tolerable limit by increasing the daytime load. Energy can be supplied directly to the daytime loads from the solar PV system except in rainy or foggy days. Thus, higher storage requirements can be avoided.

4.4. Night time load

The main challenge in running a minigrid is when electricity generation from solar PV declines in the early evening. To maintain the supply of power after the sunset, it is essential to continue the power supply either from a storage system or by running a diesel generator. On the other hand, the main load demand rises in the evening because maximum lamps and other electric gadgets turn on together. So, it is imperative to calculate the night time load perfectly to determine the optimum size of the storage system and the run time of the generator.

4.5. Peak load

In general, the peak loads are experienced in the evening. The size of off-grid inverters and generators are dependent on the night load.

4.6. Seasonal variation

During summer, the demand for electricity is at its highest as cooling loads add to the lighting load. Moreover, the run time of the cooling loads are much higher than that of the lighting loads. On the contrary, during winter, the cooling load is not present. The demand for electricity is lower in winter than in summer. Furthermore, in the context of Bangladesh, cool temperatures lasts longer in rural than in urban areas. Considering these seasonal variations, the plant size varies. Taking into account all these seasonal load variations a source of power should be designed that can provide reliable power throughout the year. The graph below shows the estimated load profile in summer and winter of Bangladesh for a 200 kWp solar-diesel hybrid power plant according to survey data. During summer the irradiance is higher than in winter; on the contrary during summer irrigation demand reaches its highest. So, additional power generation from solar PV system can be used for irrigation. Fig. 4 shows the estimated load profile of a designed minigrid in the northern part of Bangladesh, where only the households and small village shops are covered. The variation in load profile in summer and winter are due to the use of cooling fans. During winter the cooling requirement is almost nil. Fig. 6 shows the estimated load profile developed for another minigrid also in the northern part of Bangladesh. In this minigrid 14 small irrigation pumps are accommodated to increase the day load and also to utilize the unused energy of winter and summer.

5. System design

Survey data show that the demand reaches its peak after sunset and it generally lasts until 10 pm. Solar power is the main source and the generator is kept as a backup or standby for such a minigrid. The daily average generator run-time depends upon the shortfall in solar energy and amount of storage in the battery bank. The solar-diesel hybrid minigrids are predominantly powered by solar photovoltaic systems. Monthly generation from PV can be determined from the hourly averaged radiation data. Hourly average expected demand data are determined from the site survey. The daytime load is considered from 8 am in the morning to 5 pm in the evening. Generally the demand of the daytime load is lower than the generated PV power, so in the battery capacity calculation the day load is excluded. The night-time load is served by stored energy in the battery through the bi-directional off grid inverters. The generator will run when the stored energy in the battery is not sufficient to serve the night load. As the system contains a diesel generator, no autonomy day is considered. Fig. 7 shows the schematic diagram of a typical solar-diesel hybrid minigrid. Main hardware of the solar hybrid PV plant consists of:

- Solar PV panels to convert solar energy into DC electricity and grid tied inverters to convert the solar energy to AC power to serve the loads.
- Off grid bi-directional inverters to provide power to the loads during night from the battery and also to charge the battery from the grid power (when the generated power from the grid tied inverters during day are more than the demand of the grid).
- Diesel generator for backup power and batteries as electrochemical storage

The number of grid tied and off grid inverters depends on the load pattern: If the day load is comparatively higher than the number of grid inverters need to be higher and in that case the day load can be directly supplied from the power generated from the grid inverters. If the night time energy demand is higher than daytime, then the number of off grid inverters needs to be of higher capacity. The solar energy needs to be stored into the battery and then needs to be inverted to meet the night load. In that case some energy will be wasted during the charging-discharging of the batteries (round trip efficiency of a battery storage system is close to 80%). On the other hand the efficiency of the off grid inverters are lower than the grid inverters. Cost of solar energy directly converted by grid inverter is much cheaper than the energy that comes via the battery. The peak load determines the capacity of the diesel generator. The size of the diesel generator needs to be higher than the peak load, so that if the systems fail for any reason, the generator should handle the peak load.

6. Cost breakup of a typical 141 kWp solar hybrid system

Fig. 8 shows the cost breakup of a typical solar-diesel hybrid minigrid system developed for rural Bangladesh electrification. The cost may vary according to the following criteria:

- Load pattern: The system sizing depends on total energy demand and also the energy demand during daytime and night time. If the night load is higher than the numbers of battery and the off grid electronics increase which in turn increases the project cost.
- Peak load: Peak load determines the size of the generator and also the inverters.
- Land and land development cost: price of land varies from site to site. The land development requirement is also varies depending upon the recorded flood level of that area and the terrain.
- Renewable Energy Fraction: The higher the renewable energy fraction the higher the capital cost of a system like this. The reliability of the renewable energy source as well as the quality of the diesel supply chain to the mingrid location are crucial aspects for the design of the energy mix.

Storage system/battery system management is the most challenging part of designing a solar-diesel hybrid minigrid system. Generally the panel warranty covers the life of the project. But battery systems are likely to be replaced twice. So, the cost of battery is the single most costly thing. While designing the battery system (In the case of Bangladesh the tubular positive plate industrial grade lead acid batteries are used as storage medium). The battery system design needs to consider the following aspects: the limitation of charging and discharging currents limits the design flexibility; limitations of depth of discharge of battery operation

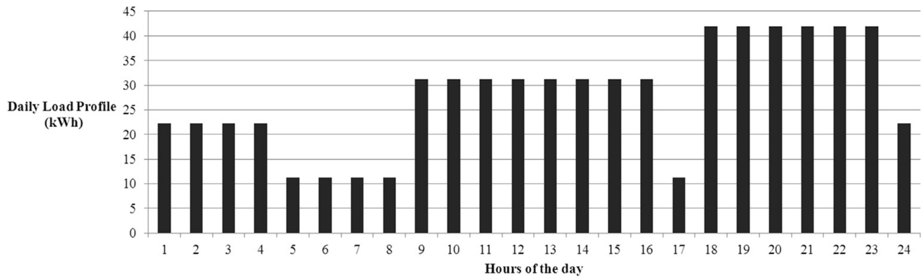

Fig. 6. Estimated load profile of dry season (November to June) of an off-grid area by 148.5 kWp solar PV hybrid minigrid where 14 irrigation pumps are suitably connected to the minigrid for better utilization of the solar power [866 households, 116 shops in rural market, 10 primary schools and mosques and 14 irrigation pumps of 2 kW power rating].

increase the size of battery bank; and the fact that higher ambient temperature reduces the designed battery life.

Adding a diesel generator in the system provides the following advantages. For instance, the increased reliability of power. This is followed by reducing storage requirement, less autonomy requirements, and the reduction of capital expenditure (reduced battery size reduces the project cost).

7. Quality control and monitoring

The minigrid systems should be operated by trained personnel. If adequate operation and maintenance staff is not provided, the plant can be on high risk. Though Bangladesh is experiencing overwhelming success in its SHS based rural electrification program, the program suffered technical difficulties (Chowdhury et al., 2011). As several minigrid are on the pipeline for installing, a very strong quality control mechanism should be developed in Bangladesh. Proper monitoring scheme and guideline is necessary for the proper operation of a solar-diesel hybrid minigrid system.

8. Conclusion

This paper shows how the SE4All goals can be translated into a resource-efficient action for the case of minigrids in Bangladesh. The SE4All intentions are applied in the minigrid design through a) assuring reliable energy access, b) utilizing a high renewable energy fraction and c) by incentivizing the use of energy efficient appliance technology. The identified critical design principles including a detailed survey based demand analysis that identifies potential variation in the load between day and night and within seasons. On the basis of that, the design of the technology is undertaken whereby a strong focus is set on the support of productive

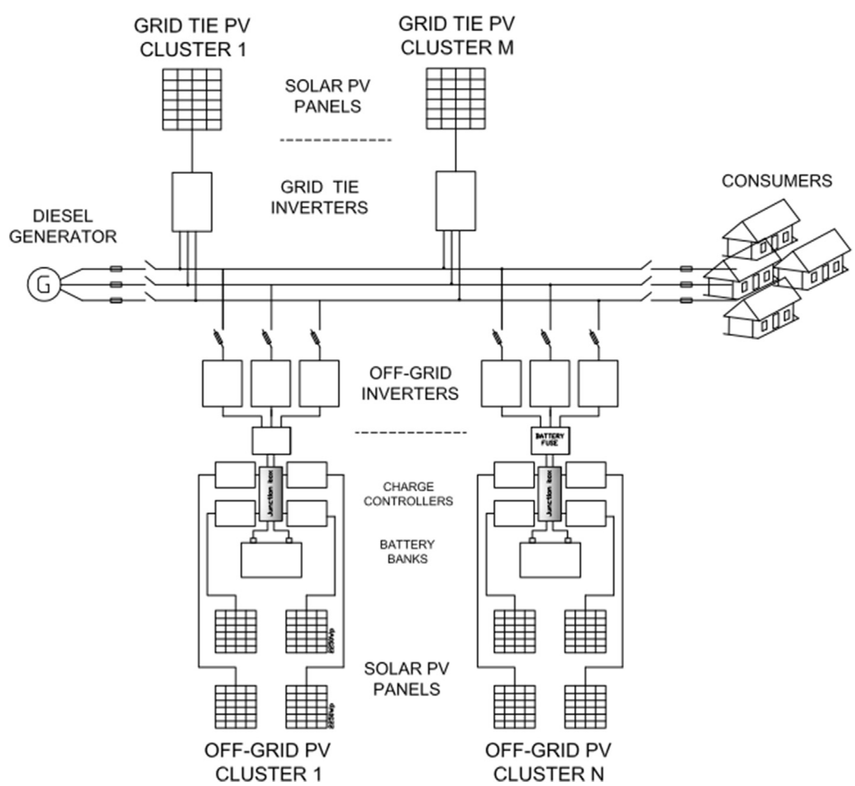

Fig. 7. Single line diagram of a typical 150 kWp solar-diesel hybrid minigrid system.

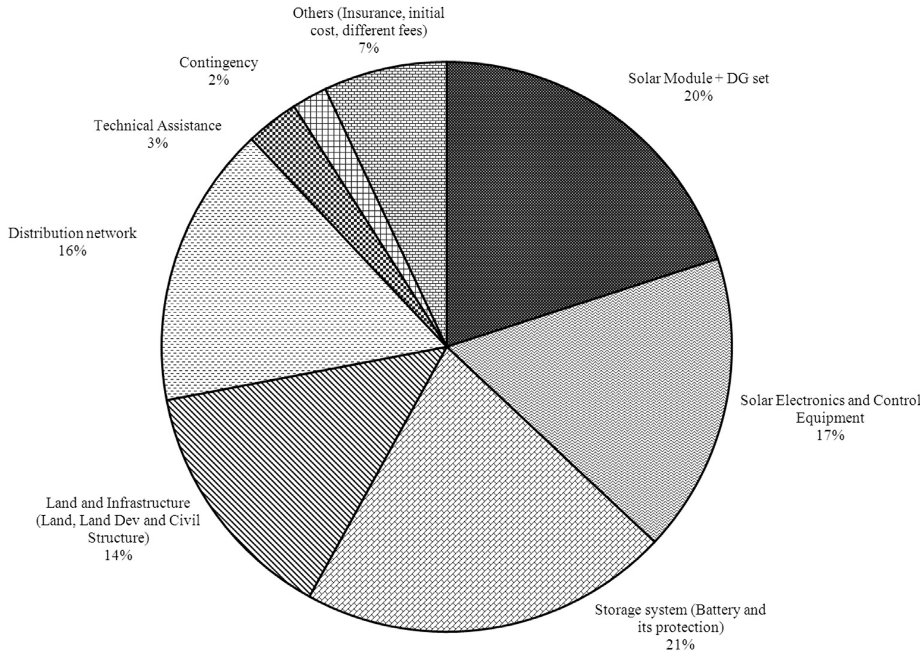

Fig. 8. Cost breakup of the 141 kWp solar-diesel hybrid minigrid developed for electrification of Bagha Upazilla of Rajshahi district ["DG" stands for "Diesel Generator"].

use, in particular as smart demand response systems that are activated during daytimes when supply from solar energy is high. Financial resource efficiency is achieved by applying a lifetime cost analysis for the battery storage system that is large enough to cater for the night load (without autonomy days). A high penetration of renewable energy is possible despite the small battery size as a diesel generator is available for backup services.

Minigrids can be important tools to reach the SE4All goals in a mutually beneficial way since they employ renewable and energy efficient technologies to a large degree combined with the potential of helping millions of people to gain better electricity services in terms of higher tiers in the multi-tier framework. The decentralised access to energy, as minigrids cater for, can lead to new opportunities for gainful employment and trade. Therefore, in the context of an ethical framework for sustainable development, policy-makers should pay more attention and offer more support for the use of minigrids. This is not only important for socio-economic reasons, but especially in order to address concerns about global warming and climate change, and in order to minimise the environmental impacts of conventional energy generation methods. If we want to maximise the options in the field of energy supply and energy use, at the same time that we take into account the needs of future generations, then minigrids need to be pushed into the front line of energy policy, changing the way we address our current and future energy needs.

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Chapter 4

The Battle of Edison and Westinghouse Revisited: Contrasting AC and DC microgrids for rural electrification

"We need a global clean energy revolution, a revolution that makes energy available and affordable for all."

- United Nations Secretary-General Ban-Ki Moon, 2011

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The Battle of Edison and Westinghouse Revisited: Contrasting AC and DC microgrids for rural electrification

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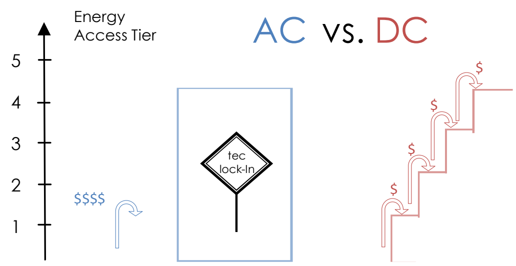
Abstract

As distributed renewable energy (DRE) systems expand rapidly as a means of electrification for the off-grid population, the debate over the relative merits of alternating current (AC) versus direct current (DC) based systems has intensified. Given that most of the DRE generators as well as batteries deliver DC power and that the majority of appliances being used in rural areas (can) run on DC, it follows that DC-based microgrids are a logical and efficient choice as a solution for electrification. This hypothesis is analyzed in detail for a developing country setting applying the new multi-tier methodology for measuring energy access as introduced by the World Bank. Further, a case study is conducted on an innovative DC nanogrid in Bangladesh as a real world test of practicability. Results show that a re-evaluation of current safety concerns is needed as both theory and commercial practice are superior for DC systems. Further, system performances and efficiency results as well as higher affordability of DC-based microgrids, lead to their comparative advantage. Despite these advantages, the dissemination of DC microgrids still lags far behind AC microgrids. This is due to a number of reasons. Despite a long history, microgrid implementations remain un-standardized and are still in their infancy. Given this relative immaturity, markets tend towards what is already familiar, such as the AC configuration and the prevalence of AC-based appliances that dominates large-scale utility grids, as originally promoted by Westinghouse. Thus, despite the 'new market' that microgrids represent, we see strong signs that lock-in effects from the AC power still prevail despite the advantages of DC power and despite the favorable greenfield environment of rural electrification in the Global South.

Keywords: rural electrification; DC; microgrids; multi-tier approach; Bangladesh

Graphic for Manuscript



Source: Groh and Kirchhoff (2015)

Introduction

"When two or more increasing-return technologies 'compete' […], for a 'market' of potential adopters, insignificant events may by chance give one of them an initial advantage in adoptions" [1]. This interaction can be clearly seen in relationship observed in the past for a variety of competing technologies. One classic example is that of the standard keyboard layout designed as QWERTY by Christopher Sholes and more ergonomic configurations. Despite the fact that it has been proven not to be the most efficient layout of typing, it has set the standard and a transition is not in sight [2]. These incumbent roles -often a chance occurrence- early lead in adoption, and can therefore "corner the market of potential adopters, with the other [potentially superior] technologies becoming locked out" [1].The cost and risks of the technology transition can simply be too high given that an initial infrastructure has already been deployed. This insight also applies to the historic "battle of the systems" by Edison and Westinghouse [3]. While Edison promoted direct current (DC)[1] for electric power distribution, Westinghouse commercialized Tesla's invention of alternating current (AC)[2] generation and distribution equipment and managed to corner the market [4]. Recent trends, however, may change these dynamics dramatically, re-asking the question of who was right, Westinghouse or Edison, and it may very well turn out that they both were.

[1] "Alternating Current (AC) is a type of electrical current, in which the direction of the flow of electrons switches back and forth at regular intervals or cycles. Current flowing in power lines and normal household electricity that comes from a wall outlet is alternating current" [38]. Available under: http://ec.europa.eu/health/scientific_committees/opinions_layman/en/electromagnetic-fields/glossary/abc/alternating-current.htm. Last accessed: March 20, 2014.

[2] Direct current (DC) is electrical current which flows consistently in one direction. The current that flows in a flashlight or another appliance running on batteries is direct current [41]. Available under: http://ec.europa.eu/health/scientific_committees/opinions_layman/en/electromagnetic-fields/glossary/abc/alternating-current.htm. Last accessed: March 20, 2014.

Today in the Global South distributed renewable energy (DRE) technologies are experiencing a great push as a means of electrification for off-grid populations [5], contributing to working against a widening of a supply and demand gap triggered by significant increases in energy use and increasing expectations in the last decades in developing countries [38]. Dissemination occurs through so-called Pico PV (photovoltaic) systems, small mobile solar systems for lighting and charging communication electronics, through Solar Home Systems (SHS), individual household-scale energy systems with PV generators and batteries used for lighting, communication and entertainment devices, as well as through microgrids. "[M]icro-grid refers to systems of very small scale, with power output ranging from hundreds of watts to a few kilowatts, typically with fewer than 150 household customers" [6]. It thus forms part of the family of isolated grids generally referred to as mini-grids, where much innovation has taken place in the past decade and that do not stress scarce water resources in the Global South as these decentralized systems do not require significant cooling of thermoelectric power generators [40]. According to Arthur [1], lock-in occurs when changing costs are prohibitive. Consequently, in a greenfield scenario the phenomenon should apply to a much lesser extent at the point of decision for a new technology track to embark on. Having established that, the battle of currents is hence newly fought when transferred to electrification in the Global South. By definition, the targeted population in rural electrification schemes lacks any electricity transmission lines. Therefore, a technology-driven lock-in possibility for AC power cannot occur through the availability of central grid infrastructure, but lock-in resulting from best current practices and experience based on the availability or dissemination of AC vs. DC appliances certainly has, and can, take place. There has been, however, a recent change in terms of availability of these products both in the Global North, thanks largely to the recreational vehicle industry, as well as in the Global South, based on newly created demand [7]. There is a robust set of appliances and other household items that are designed to run on either 12- or 24-volt DC; which are readily available. Furthermore, renewables promise to serve as the primary source of electricity in off-grid areas in the future [7]. This trend is triggered by a combination of two factors. First, people that lack a certain level of energy service quality (e.g. lack access to the national grid) spend more money on energy relative to their total income than people who enjoy better energy service quality, and thus they have a higher willingness to pay for energy [8]. Secondly, decreasing photovoltaic panel prices in the world market played largely in favor of an accelerated deployment of solar energy technologies [9]. As an example, at the time when significant SHS growth took up in Bangladesh, prices for systems were two times higher than the present day price.

In addition to the increasing availability of DC appliances, the majority of DRE generators, as well as the batteries used to store the generated power both operate with DC power. These factors support the argument that emerging infrastructure for rural electrification should equally be DC-based in order to guarantee system efficiency. In literature, there is surprisingly little attention paid to theoretical and practical comparisons between DC and AC grids focused on service delivery in a developing country context. The hypothesis of DC as the preferred choice under the given context is analyzed in detail applying the new multi-tier approach to measuring energy access as introduced by Energy Sector Management Assistant Program (ESMAP), which is expected to form the new standard for the evaluation of different degrees of electrification. The multi-tier framework assesses energy access along several attributes (e.g. reliability, affordability, etc.) [25]. Indicators to determine the attributes are either binary or measured along a graded scale. It needs to be carefully noted though that the framework is a work-in-progress and continuously updated which is why for the purpose of this paper it has merely been used as a guide for a first comparative assessment of AC and DC microgrids along these proposed attributes.

Functionality of DC microgrids

The UN General Assembly has declared the years 2014-2024 to be the "Decade of Sustainable Energy for All"[10], underlining the importance of supporting the roughly 1.3 billion people living without access to electricity and achieving the Millennium Development Goals [26]. The "Energy for All Case" expects that only 30% of rural areas can be electrified via connection to centralized grids, whereas 70% of rural areas need to be connected with decentralized systems, the great majority of them with microgrids [11]. Yadoo & Cruickshank [12] estimate that about half of the off-grid population today could be best supplied with decentralized microgrids. For the sake of clarity we restate two possible definitions for microgrids [4]:

> *"Microgrids are electricity distribution systems containing loads and distributed energy resources (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded" [13].*

"A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode"[14].

Key attributes of both definitions, and many others, are the distribution of energy resources, they can as a single controllable entity and the possibility of grid interconnection. Despite these predictions and the fact that microgrids have been employed for village electrification already for over 30 years, literature not entirely focusing on technological aspects still remains fairly scarce leaving the field often to grey literature [15]. This is only gradually changing with recent publications by major development institutions such as Fraerson & Tuckwell [16], Schnitzer et al. [17], and Tenenbaum et al. [6]. Still, literature focuses almost entirely on financial, managerial and technical criteria, e.g. Ulsrud et al. [18]. There is surprisingly little attention paid to theoretical and practical comparisons between DC and AC grids focused on service delivery in a developing country context with some notable exceptions discussed below. Tenenbaum et al. [6] stress the point that AC is the norm despite possible advantages of DC based on lower balance-of-system costs and higher efficiencies. On the other hand, they claim disadvantages for DC as most appliances use AC and low-voltage DC suffers from significant line loss whereas high voltage DC suffers from safety issues. Moreover, Khan [19] makes the case for DC microgrids in Bangladesh pointing out that despite the success of the SHS model, it has its limitations in terms of usage quality, quantity and diversification. The concept they have put forward is to build a DC grid connecting solar PV arrays and households which will have their own battery storage–to be charged by the DC grid. Groh et al. [20] suggested a similar case for Bangladesh where a DC microgrid is suggested to be constructed from the existing SHS in the market in Bangladesh, a concept coined as swarm electrification. Another case can be made in Kenya, where the rapid and early growth of SHS [21] [22] resulted in the dramatic expansion of a market that while meeting the needs for basic services, did not rapidly meet the interests and demands for income-generating small-scale commercial activities. While it is not possible to prove this in the natural experiment was as is the largest off-grid solar energy market in Africa, could have been served differently, and in some assessments, more effectively, with a greater emphasis on DC networks [23].

The evolution from SHS deployment to local microgrids is partially dependent on the expansion in generation capacity from a single generator technology (the PV panel) to a more diverse set of generators. This allows for the flexibility of distributed placement of PV panels to be connected to the grid directly (i.e., PV panels of different power capacity can be placed in various locations such as rooftops instead of placing them at a single site as done in centralized mini-grids). As such, the scheme can be considered as a clustered form of SHS, where the generated power surplus during the higher sunshine season is large enough to be used for developmental activities such as irrigation, rice de-husking, small-scale flour mills, etc. Further, Sarker et al. [24] make the case that reduction in energy losses, easy system interconnection of PV and the existing practice of DC appliances in off-grid areas all favor DC systems. This is particularly true for developing countries where income levels are low and markets are highly cost-sensitive. Reduction in cost even by a small percentage can make a big difference as far as the dissemination of the technology is concerned.

The goal of the following sections and of the papers in this collection is to clarify the need for further in-depth analysis of AC vs. DC microgrids.

Contrasting AC and DC microgrids along a multi-tier approach

ESMAP's widely discussed framework of a multi-tier approach to measuring energy access is shown in Figure 1 below. The new approach defines energy access as "the ability to avail energy that is adequate, available when needed, reliable, of good quality, affordable, legal, convenient, healthy and safe, for all required applications across household, productive and community uses" [25]. Most of these attributes vary in a continuous manner and thus are amenable to a tiered measurement reflecting the degree of an energy service quality to a much better degree than previous approaches and making it an ideal tool to run a comparative analysis between AC- and DC-based systems for rural electrification purposes.

Figure 1: Multi-tier approach to measuring energy access

	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Capacity	No electricity	1-50W	50-500W	500-2000W	>2000W	
Duration	<4hrs	4-8hrs		8-16hrs	16-22hrs	>22hrs
Reliability	Unscheduled outages				No unscheduled outages	
Quality	Low quality			Good quality		
Affordability	Not affordable		Affordable			
Legal Standing	Not legal			Legal		
Convenience	Not convenient				Convenient	
Health & Safety	No				Yes	

Source: Angelou, 2014, adapted by the authors [25]

Below, a comparative analysis is performed based on the evaluation criteria shown in Figure 1.

1) Capacity

The capacity of the DC microgrids is in the kW range. Because the technology is able to power low and medium power tools it falls into tiers 3 and 4. AC mini-grids can serve the same range, but some are designed even for mining sites, hence high power tools (tiers 3 to 5).

2) Duration

The duration of usage depends on the number of users and their corresponding load profiles. Essentially there is no difference between AC and DC microgrids other than the fact that even very small loads such as a single light can be powered for many hours per day at low losses with a purely DC source. Some AC mini-grids are not operated during night hours due to the low relative power consumption (mainly street lights), which is associated with high relative losses in inverters and generators (low load factor).Hence, the daily operation time varies from site to site for both AC and DC grids, but similarly sized DC grids can be expected to not only cater to business usage of a minimum eight hours per day, but to provide a 24/7 service, without the low load factor restrictions of an AC grid.

3) Reliability

The reliability of DC microgrids can be very high as no frequency synchronization is required, and therefore no complex inverter electronics and timing devices are needed. Additionally, modular growth of DC generators and storage devices is possible, improving the ability to meet a changing demand. Unscheduled outages should not occur, allowing for a tier 4 rating. AC grids might also receive a tier 4 rating, as limited runtime during night hours can be considered a scheduled outage. However, the reliability of the AC grid may be compromised with increasing demand on the grid over time, as AC grids pose increased challenges in the integration of new generators and expanded storage [19] [6].

4) Quality

The quality of electricity is a widely discussed topic and comprises different attributes including the reliability of service, the stability of the voltage, the ability to power large loads and very low down-time for maintenance and repairs. These criteria can be met both with DC as well as AC mini-grids and hence allow for a tier 3 rating.

5) Affordability

AC mini-grids still face challenges to implement CAPEX-recovering tariffs that are attractive for both private investors and end-users. DC microgrids, however, are able to tackle a similar target group to SHS solutions, which have a strong track record of affordable energy access. In comparison to AC mini-grids, inverter technologies are not required. Energy delivered as AC is now consumed as DC. In computers, consumer electronics and many small appliances as well as CFL and LED lighting the actual power consumed is DC.[3] That means there is a conversion loss that adds to the energy usage. Similarly there is energy loss in converting from the DC produced by the photovoltaic systems on the roof to AC and then in many cases back to DC. In these cases conversion losses rapidly mount. Although conversion from AC to DC is relatively simple and inexpensive, conversion from DC to AC is much more complicated and the hardware is still fairly expensive in the lower watt range. The price of solar PV in the present market is set to be less than USD 1.0 per Wp [29], but the cost of a small-scale inverter is about the same. This is a comparatively high price to pay for the conversion, even if we ignore the conversion losses.

Against the background that currently, more than 50% of the electric load in buildings goes to DC-powered electronic devices [29], the high costs for inverter equipment and over-sizing the generation and storage systems to compensate for losses, makes AC systems even less attractive.

However, because DC microgrids still need to prove their affordability on a large scale, this category can be rated tier 3 to 5 and is depending on the size of the system.

[3] The LED lighting case has been closely examined by Thomas et al. [28] indicating that DC systems show a 12% decrease in levelized annual operation costs for PV-powered LED lamps in office buildings than AC systems [2012].

6) Legal Standing

In regard to a legal framework, DC and AC mini-grids face similar challenges. In many countries, licenses for generation and or distribution must be obtained, which can translate into high transaction costs. Thus, this category depends on the country of application; in summary tier 2 or 3 may accurately reflect this issue.

7) Convenience

DC microgrids provide the ability to power electric loads of various power and daily energy requirements allowing for convenient usage. Tier 4 is the rating in this category as some businesses would still prefer an AC outlet for standardized machines. Increasingly DC motors have become available, which may alter this preference. A convenient advantage of e.g. 48V DC transmission line over AC is the fact that electricity theft becomes less of an issue as the transmission line output cannot be directly used.

8) Health and Safety

Safety in DC systems has been a controversial discussion and a full risk-based performance analysis as suggested by Gabber et al [30] is still to come. It has been emphasized that for DC systems, “arcing in switches” is a key safety concern [6]. However, there is strong evidence in literature demonstrating adequate DC protection schemes and devices [31] [32] as well as experience with DC systems in the communications, recreational vehicle and PV industries. ESMAP defines the requirement in the *health and safety* category as "the energy system has not caused in the past, and unlikely to cause in the future, harm from burning, injury, electrocution, air pollution or drudgery" [25], and given that DC microgrids have safely been in operation for years [31], it can be rated with the same tier as AC at level 4. Both AC and DC pose a risk of electrocution and injury, but DC poses a lower risk of severe injury [33]. Both AC and DC systems require adequate protection schemes and technologies that are sized according to the requirements of a particular site. Circuit breaker devices [31] as well as protection schemes and structures are available for both AC as well as DC systems [34]. In addition, solid-state and hybrid (semi-mechanical) circuit breaker have been tested [35]. Furthermore, an isolated (ungrounded) DC system [32] also presents safety advantages, namely the inability to be electrocuted by touching a single conductor.[4] In an isolated or “floating” system, both conductors must be touched at the same time in order for a foreign body to complete the circuit loop and thereby cause

[4] Grounding may become necessary though considering safety and protection of the system during thunderstorms.

electrocution. In a grounded AC system, however, touching a single conductor can complete the circuit loop, because the current has a return path through the body and through the earth itself back to the point of system grounding.

General

In general, DC grids have the following advantages over AC grids:

- No need for synchronization between different sections of the network.
- Lower cost and fewer pieces of major equipment required as no inversion from DC to AC is required.
- No skin effect at the switching frequency of the SMPS converters, no inductive and capacitive loss and thus less transmission loss compared to AC grid system for the same load condition.
- Two line instead of three phase plus ground distribution required for DC systems.
- No continuous charging current, no reactive power loss, no need of power factor improvement devices and less switching transients.
- DC appliances generally have higher efficiency than AC appliances.

Table 1: Multi-Tier Assessment Overview

	AC mini-grid	**DC mini-grid**	**Δ**
Capacity	3...5	3…4	-0.5
Duration	3…5	5	+1
Reliability	3…4	4	+0.5
Quality	3	3	+/-0
Affordability	1...3	3…5	+2
Legal Standing	3	2…3	-0.5
Convenience	4...5	4	-0.5
Health & Safety	4	4	+/-0
Overall sum	**28**	**30**	**+2**
Overall average	**3.5**	**3.75**	**+0.25**

Overall

The overall scores, as shown in Table 1, reveals that AC and DC mini-grids are both highly attractive rural electrification technologies.[5] DC systems still lack behind in regard to convenience for usage in power tools and are not yet fully on the radar of policy makers. Nonetheless, high affordability, efficiency and flexibility are clear advantages of DC microgrids. Generally speaking, good infrastructure can be evaluated based on the four A's: affordability, accessibility, acceptability and availability [37]. The following case study show cases an illustrative case from the end-user perspective where these features are examined.

Case Study and Discussion: End-User Perspective in a DC nanogrid in Bangladesh

In Bangladesh 40% of the population has no access to the national grid representing 65 million people [World Bank, 2013]. In the rural areas, the un-electrified population is 58% [39]. SHS, currently consisting of a 20Wp to 85Wp solar panel, battery, and charge controller, have begun to electrify Bangladeshi rural communities [40]. Close to three million SHS are already installed through microfinance schemes implemented by so-called Partner Organizations (POs), who are expanding their customer base at a rate of 65,000 systems per month, making Bangladesh the fastest growing SHS market in the world. However, the use of SHS has certain limitations in terms of daily time of usage –often limited to 4 to 5 hours per day–as well as lack of variation in compatible appliances. As a consequence, new models are starting to find their ways into the Bangladeshi off-grid market. One of them is the so-called DC nanogrid implemented by *SolarIC*[6], a local company that made its mission to reduce per unit cost of renewable energy through community energy solutions based on DC. The DC nanogrid takes advantage of the fact that houses are frequently clustered together in rural areas in groups of about 50 houses within a diameter of less than 500m. In the nanogrid system, a basic 3kWp PV system is installed in a small cluster of households within a short radius of each other (ideally 500m) and power is distributed to the households from this system. The centralized generation and storage unit of this system operates on a 48 VDC level. However, the distribution to the households is via DC/DC converter at 220 V DC, just as the end-use voltage, which offers the user the option to use most common AC appliances such as mobile phone charger, televisions, computers and other

[5] c.f. "[…] mini-grids typically provide service up to Tier 3 or 4" [6].
[6] Solar IC: http://www.solar-ic.com/newsite/about-solaric/.

electronic devices. Such appliances are insensitive to DC or AC and can run on DC power, as long as the voltage matches the required input voltage of the device, normally ranging from 90 V to 270 V.

The individual case study is based on the experience of Aswini Barua[7], a local poultry farmer in a village called Lohadi in the region of Kapasia which is about a 100km to the north of Dhaka.[8] Lohadi is considered an off-grid village although the national grid runs only two kilometers nearby. Mr. Barua has two chicken cages both hosting about 800 chickens and lives from the sales of the eggs. Total monthly revenue amounts USD 2,070 per month at a monthly accumulated cost of USD 1,670. In order to increase productivity, chickens are exposed to artificial light 24 hours a day. Until recently this power came from a diesel generator. Capital investment cost was USD 362 with running diesel costs of up to USD 50 per month. Mr. Barua also has a SHS for residential lighting and entertainment purposes, but a couple of months ago he decided to become connected to the village based nanogrid that supplies his house and poultry farm with electricity 24/7 at a price of Tk. 0.1 per Watt-Hour (Wh) as the actual tariff charged for the energy provided by the nanogrid. The nanogrid consists of a 3kWp PV generation capacity with a 34kWh battery bank that is operated by a local entrepreneur. There is a 3kVA standby generator only to be used occasionally to support the system during inclement weather condition. The system has been running for more than nine months interconnecting 53 households and 4 poultry farms based on 220V DC gridlines running in cabling buried 10-15 inches underground. Payment is organized by the local entrepreneur and facilitated through an advanced pre-paid meter with an automatic maximum load factor switch-off function. Operation and maintenance cost comparisons between former diesel generator and the new nanogrid shows a decrease from USD 50 to USD 22 monthly. This implies a 56% decrease in monthly operating electricity costs or a saving of USD 36 each month if a linear depreciation of CAPEX (USD 8 per month) is taken into consideration. Please refer to table 2 in the appendix for a brief overview of these figures in its original currency Taka. Based on these numbers Mr. Barua is currently building up a third cage which will equally be supplied from the nanogrid. There are four more poultry farms in the wider village. The diesel generator and SHS are currently no longer in use. Based on this analysis, the concept meets the criteria of good infrastructure in terms of complying with the 4A

[7] Original name was changed.

[8] The following information is based on the indications by Mr. Barua himself in an interview led on March 7, 2014. Mr. Barua agreed on the publication of his data which has been confirmed by Solar IC staff. Nevertheless, data should be considered indicative but still underlining the business case and practical feasibility of the technology. All numbers have been converted to UN Operational Rates of Exchange (Tk. 77.25 as of March 1, 2014] and later rounded for reasons of clarity.

scheme despite certain limitations as discussed below. It builds its network directly into the rural areas, making it accessible for the local community. It remains to be discussed though how rural you can go under that scheme given that a local operator needs to be found in the respective area. It definitely results in favorable economics based on based on the calculations made versus the status quo (affordability). Again, however, it is arguable how inclusive the scheme is, given the USD 50 connection fee without any (micro-) financing option. The nanogrid can count on a 24/7 electricity service using a variety of highly efficient appliances (availability) and thus far receives a high degree of local acceptance.

Current trends in available technologies for off-grid electrification tend to favor DC microgrids. This statement finds support in a comparative analysis between AC and DC based microgrids based on a multi-tier approach to measuring energy access. It is essentially a re-evaluation of current safety concerns, an increasing availability of low power consuming appliances running on DC and most importantly system performances and efficiency leading to higher affordability. Despite this, the dissemination of DC microgrids still lags far behind AC microgrids. This may be based on a number of reasons. Despite a long history, implementations of microgrids are still in its infancy. Given this prematurity, markets tend to stick with what is already familiar, including the configuration of AC utility grids originally promoted by Westinghouse. This leads to the conclusion that lock-in effects for AC power must still prevail despite the advantages of DC power and the greenfield environment of rural electrification in the Global South. This lock-in takes effect, however, not based on prohibitive changing cost, but on a lack of confidence and knowledge transparency of the alternatives. Therefore, the authors encourage researchers as well as practitioners to step forward into this field and share the latest research and implementation results of DC power.

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Appendix

Table 2: Substitution effect in nanogrid (original values)

	Diesel Generator	**Nanogrid**
CAPEX	Tk. 28,000 (diesel gen. cost)	Tk. 4,000 (connection fee)
Running cost per month	Tk. 3,950	Tk. 1,750
Supply time	6h per day	24/7
Fuel volatility	high	none
Total revenue per month	Tk. 160,000	
Non-energy costs per month	Tk. 102,600	
Total electricity cost per month	Tk. 3,950 + Tk. 778[a]	Tk. 1,750 + Tk. 111[b]
Profit per month	Tk. 52,672	Tk. 55,539
Profit margin per month	32,92%	34,71%

[a] expected lifetime of a 24/7 used diesel generator is about three years given 26,280 of running time, cost per month calculated based on linear depreciation
[b] for comparison a lifetime of three years is expected also with linear depreciation

Chapter 5

You are what you measure! But are we measuring it right? An empirical analysis of energy access metrics

To me, the poor are like Bonsai trees. When you plant the best seed of the tallest tree in a six-inch deep flower pot, you get a perfect replica of the tallest tree, but it is only inches tall. There is nothing wrong with the seed you planted; only the soil-base you provided was inadequate. Poor people are bonsai people. There is nothing wrong with their seeds. Only society never gave them a base to grow on.

- Muhammad Yunus, 2008

You are what you measure! But are we measuring it right? An empirical analysis of energy access metrics

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Abstract

Measuring energy access through binary indicators is insufficient, and often, even misleading. In this work, the SE4ALL global tracking framework, and the recently introduced ESMAP multi-tier approach, is critically discussed and tested by applying it to questionnaire based primary data from rural Bangladesh. The performance of different energy interventions is evaluated using the new tier framework. The challenges in its application lie in reliable data collection, adequate gradation of indicators, and design of an effective algorithm for tier assignment based on a specified set of attributes. The study shows access measurement is highly sensitive to changes in parameter values, the application of different algorithms, and data availability. The results reveal a clear trade-off between capturing the multi-dimensionality of energy access and the simplicity of an easy to use global framework. Suggestions to improve the measurement framework are made and conclusions are drawn for possible implications of applying the tier framework to different energy service offers in the rural Bangladeshi market. Strengths and weaknesses of the present measurement scheme are discussed and country specific results interpreted through a targeted gap analysis that provides insights for future policy.

Keywords: energy poverty; Bangladesh; energy access; electrification; multi-tier approach

0. Introduction

Despite increasing rhetoric and action in support of the sustainable energy for all (SE4ALL) goal of achieving "universal access to modern energy services by 2030" [Ki-moon, 2011], there are still at least three issues that remain, at best, vague. First, what does universal energy access actually mean? Second, how do we actually get there? And third, if we don't have an answer to the first question, how will we even know at what point we got there? Only what gets measured is what gets done.

Counting connections to the grid is an insufficient measure of energy poverty [AGECC, 2010; Practical Action, 2013; IEA/WB, 2014]. In fact, it can even be highly misleading. As an example, Bangladesh just celebrated installing more than 3.5 million solar home systems (SHS), representing by far the highest penetration of SHS in the world [IDCOL, 2014]. Ignoring for a moment the number of SHS that are in areas officially counted as electrified and assuming an average family size of five, this number represents 25% of Bangladesh's off-grid population that are equipped with some form of electricity. Yet, not a single one of these systems is reflected in the national energy poverty statistics. Meaning that today, they represent zero progress towards the SE4ALL goal, because the baseline of the global tracking framework is still the binary indicator measured as the percentage of people living on and off the grid, respectively. The reason behind this is that currently available global databases only support a binary global tracking of energy access. The good news is that the World Bank's Energy Sector Management Assistance Program (ESMAP) has developed a new framework for measuring energy access: the multi-tier framework [Banerjee et al., 2013], that has been heralded as a new "milestone" in energy measurement [Bensch, 2013]. The multi-tier framework assesses energy access along several attributes (e.g. reliability, affordability, etc.) measured either by binary indicators

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or along a graded scale. Performance on a combination of these individual attributes determines the assignment to a specific tier, which in turn reflects the level of electricity access of the object of investigation. But does the candidate framework[1] uphold its promise of measuring a “continuum of improvement, based on the performance of the energy [service] supply” [ESMAP, 2014]? It is now be up to the scientific community to support the operationalization of the ambitious energy access for all by 2030 goal through rigorous evaluation of the new measurement framework. In September 2015 the Sustainable Development Goals (SDGs) will be agreed upon in New York [UN 2015]. This time, unlike in 2000 during the formulation of the Millennium Development Goals (MDGs), chances are high that energy for all will be included as an explicit goal. Its inclusion makes it even more important to have a robust set of measurement tools to track progress towards its achievement. This paper adopts the recommended ESMAP framework and applies it to the case of Bangladesh, assessing electricity access in a sample of 230 households and microbusinesses[2]. It is the objective of this analysis to provide feedback on the multi-tier framework’s design, and suggest potential improvements, as well as to discuss its wider implications against the backdrop of current electricity access intervention programs in Bangladesh.

1. Measuring energy access

1.1 Efforts so far

The predominant criterion for measuring energy poverty/access is still the binary indicator estimated as the ratio of people lacking access to an electric grid connection, and dependent on traditional biomass for cooking, to the total population, respectively [IEA, 2010]. At times these measures are supplemented by estimates of the number of people who suffer from an intermittent electricity supply, although “intermittency” lacks a clear definition [AGECC, 2010]. Several attempts at developing alternative criteria, applying a uni-dimensional approach, have been put forward to measure energy poverty. These range from minimum energy consumption thresholds [Modi et al. 2005] to income-invariant energy demand measures [Barnes et al. 2011]. At the same time, some multi-dimensional approaches have also been put forward, such as the Multidimensional Energy Poverty Index (MEPI) [Nussbaumer et al. 2012], or the Total Energy Standard (TEA) [Practical Action 2012]. Recent reviews and comparative studies on different energy poverty indices include those by Pachauri [2011], Khandker et al. [2012] and Bensch [2013]. Many of the current indicators measure electricity as an output (e.g. lack of access) rather than an outcome, which better reflects service needs and welfare gains [Pachauri & Spreng, 2011]. This is mainly due to the fact that an accurate measurement of the service level is very challenging given the diverse nature of energy in terms of different forms of generation sources, technologies, a wide spectrum of applications, phenomena such as fuel stacking, and heterogeneous target groups (household, micro-businesses and hybrid forms). Nonetheless, despite high data requirements, “there is a growing consensus that measurements of energy access should be able to reflect a continuum of improvement” in the services it delivers [IEA/WB, 2014].

It is generally believed that electricity is the preferred choice for lighting and running appliances. From a user perspective, it should not matter where the electricity is coming from unless social status symbols and connotations are at play (e.g. perception of SHS as second class electrification option vs. the image of the grid as providing full power access) [Schützeichel, 2015]. What should really matter is the quality of the electricity service[3] provided and this is also what should be measured. Quality can be defined here as “the characteristics of a product or service that bear on its ability to satisfy stated or implied needs” [ASQ, 2015]. If we look at poverty as an “absence of sufficient choice” [Sen, 1999], according to the capability approach, we need to pin down individual welfare components and assess how they interact as multidimensional causes of development and deprivation. For instance, using the concept of an energy poverty penalty, Groh [2014] shows how a lack of access to affordable energy services, a deprivation, can lead to a situation where people are trapped -or at least delayed- in their capability to achieve welfare improvements. The candidate multi-tier metric put forward by ESMAP reflects a multitude of the research cited above and promises to set a new benchmark, while being

[1] Please note that the candidate framework is still subject to changes as it continues to be refined. Institutions other than ESMAP are also developing alternative multi-tier frameworks to measuring energy access (e.g. EnDev, 2011). This paper merely represents an exemplary analysis of the most advanced version of a multi-tier framework, in development today, and discusses its implications.

[2] Henceforth, all survey objects are referred to as households.

[3] The term service is used herein throughout the text in order to emphasize on the intangible nature of electricity and the on-going relationship between electricity service provider and end-user, contrary to a potentially one-time over the counter relationship of a product.

flexible to country specific targeting. Nonetheless, in order to reach consensus on the candidate composite index, a thorough testing of it is required.

1.2 The ESMAP multi-tier framework

"Defining energy poverty metrics and respective targets is a complex task" [Bazilian et al. 2010, p. 15]. These should be designed in a technology neutral way in order to allow a just energy assessment of all sources, and should further reflect the impact of all energy interventions. The most complicated part though may very well be to find an effective algorithm for the combination of individual indicators that adequately reflects an energy service offer of quality. This quality is determined by the service's ability to satisfy stated or implied needs. It is at this point that things get complex. Based on assumptions of these needs, without giving into the "we know what the poor people need" trap [Schützeichel, 2015], an effective combination of indicators needs to be designed. In the multi-tier framework these needs have been defined for seven attributes, namely capacity, duration, reliability, [technical] quality, affordability, legality and health/ safety. The candidate multi-tier framework distinguishes between multiple matrices in which the attributes are defined specifically for each of the following: household electricity supply, services[4], consumption, cooking, space heating, productive applications, street lighting, as well as electricity access at the level of community institutions. The present analysis will not discuss any form of thermal energy, strict productive use or access at the community level, but focus specifically on electrical energy at the household/ microbusiness level. Figure 1.1 below summarizes the attributes as defined for the case of household electricity supply.

Figure 1.1: Simplified summary matrix of the multi-tier framework: household electricity supply

Attributes		Tier-0	Tier-1	Tier-2	Tier-3	Tier-4	Tier-5
1. Peak capacity	Power	No Electricity	V. Low Power Min 1 W	Low Power Min 50 W	Medium Power Min 200 W	High Power Min 2 kW	
	Daily capacity		Min 4 Wh	Min 200 Wh	Min 1.6 KWh	Min 4 KWh	
2. Duration	Hours per day	< 4 hrs	Min 4 hrs		Min 8 hrs	Min 16 hrs	Min 23 hrs
	Hours per evening	< 2 hrs	Min 2 hrs		Min 2 hrs	Min 4 hrs	Min 4 hrs
3. Reliability					Max 3 disruptions **per day**	Max 7 disruptions per week	Max 3 disruptions **per week** of total duration < 2 hours
4. Quality					Voltage problems do not prevent the use of desired appliances		
5. Affordability				Cost of a standard consumption package of 365 kWh per annum is less than 10% of household income			
6. Legality					Bill is paid to the utility / pre-paid card seller / authorized representative		
7. Health and Safety					Absence of past accidents and perception of high risk in the future		

Tier-rating for the household is calculated by applying the lowest of the tier-ratings across all attributes.

Source: ESMAP, 2014

Indicators to determine the seven attributes are either binary or measured along a graded scale. It needs to be carefully noted though, that given the candidate framework is a work in progress, modifications still continue to be made, e.g. the values for daily capacity have recently been upgraded, (see appendix 1.7). Nonetheless, the underlying analysis is based on the values as shown in figure 1.1 partly due to the fact that it allows for a more distinct analysis of decentralized electrification approaches (refer to section 3 for a detailed discussion). These on-going changes, however, do not undermine the analysis regarding the candidate framework's functionalities, sensitivities and further implications as analyzed in this paper.

2. Applying the multi-tier framework in rural Bangladesh

2.1 Brief Country Overview of Bangladesh

Recent data suggests that the electrification access deficit, globally, is about 17% of the world population or 1.166 billion people. Most of this unelectrified population resides in Sub-Saharan Africa and South Asia (87%), and in rural areas (85%) [IEA/WB, 2014]. With its 66.6 million off-grid people, Bangladesh ranks

[4] Henceforth, solely indicated as appliances, as the matrix really only refers to appliances and not the service itself, which would mean a combination of supply and appliances as is suggested as an alternative later (see Section 4).

third among the countries with the highest electrification deficit and has been considered a high impact country to reach the SE4ALL goals. In 1971, the year of its independence, a mere 3% of the population of Bangladesh had access to grid electricity. Today, the share has increased to almost 60%. In the last couple of years Bangladesh's GDP has been growing at a rate between 6% and 7% [World Bank, 2013]. In its development plan, titled *Vision 2021*, dated half a century after its struggle for independence, the Government of Bangladesh (GoB) has made the provision of access to electricity and achieving economic and social well-being of all citizens through a low carbon strategy a central goal [GoB, 2012]. Universal access to electricity by the year 2020, with improved reliability and quality, is the declared goal of the GoB. However, the government does not specify what it means by universal access. Should every Bangladeshi be at least tier 2, tier 3 or 4, as defined by the ESMAP framework? To highlight the complexity of measuring access, many of the on-grid population of Bangladesh, outside the capital city, may not fulfil the duration attribute for an assignment to a tier 3 level due to frequent load shedding, and a lack of access to back-up power supply. In extreme cases, such households might even get assigned to a tier 0 level, meaning no access at all, despite statistically being on-grid. At the same time, the question arises how the globally acclaimed SHS program, with its 3.5+ million installations[5] to date performs against the candidate measurement framework? The same question applies to the Rural Electrification Board's (REB) grid electrification program through its electrical cooperatives, the so called Palli Bidyut Samity (PBS) that for the most part is considered an equally great success [Khandker et al. 2009]. Moreover, IFC and GIZ recently announced the Lighting Bangladesh program with the goal to pave the way for the implementation of solar lanterns in those households that so far could not be reached through other measures [IFC, 2015].

2.2 Methods and Sample

For testing the multi-tier frameworks, a sample of 231 Bangladeshi households were surveyed. Field selection was performed in a top down way, aiming to reflect diversity in terms of geographical location, weather conditions, remoteness, and culture. One random district was drawn from the Northern (Lalmonirhat), Central (Manikganj) and Southern (Bhola) part of the country (see appendix 2). Within the respective division, an area was chosen where the Rural Service Foundation[6] has a regional office (Rangpur, Manikganj and Bhola). Within the customer base of the regional offices, the sample was drawn based on the following criteria in order to have a diverse set of users (see appendix 3 for a sampling overview):

1storder: past repayment performance,
2ndorder: system size,
3rd order: income activity.

From the stratified groups a random selection was drawn. The remaining sample was randomly chosen on-site based on vicinity criteria. Data was collected based on the generic underlying questionnaire of the multi-tier framework provided by ESMAP, with slight country specific adaptations and extensions (see appendix 4 for the detailed questionnaire). Of the total interviewed households, the following access types apply:

Table 1: Sample based electricity types

Electricity access type	**# of households**	**share of households**
National grid	69	30%
SHS[7]	107	46%
Diesel generator	12	5%
No primary access	55	24%

About 5% of the sample reported using multiple primary energy sources which is often referred to as energy/ fuel or technology stacking [Brew-Hammond, 2010]. In this paper, we test four possible decision rules/frameworks for assigning tiers to households. The simplest possible decision rule assigns a household

[5] The systems consist of a 10-130Wp panel, battery, charge controller and LED lights. The system cost ranges from BDT 8,100 to BDT 46,100, approximately, with about 10.15% down payment and the remaining balance paid in up to 36 monthly installments at an 6-12% flat interest rate (depending on the respective institution).

[6] The Rural Service Foundation is a non-profit organization of Rahimafrooz Group and a partnering organization (PO) of IDCOL's SHS program. To date, RSF has installed more than 500,000 SHS. Further information can be found under: http://rsf-bd.org/solar.html.

[7] All sampled SHS form part of the aforementioned IDCOL program.

the minimum of the tier assignments assessed for each attribute ("Supply Framework A"; appendix 1.1). A more complex version of this algorithm incorporates an alternative affordability criterion ("Supply Framework B"; appendix 1.2). A third decision rule assesses the availability of electrical appliances ("Appliance Framework"; appendix 1.3/ 1.4). A fourth decision rule measures the total energy consumption. However, because consumption data are difficult to collect, particularly for off-grid systems such as solar, we use peak capacity as a proxy ("Consumption Framework").This, however, only makes sense in the case of decentralized electrification solutions where limited capacity per individual user can be clearly defined as shown in appendix 1.5 and further discussed in section 3. Finally, we also test a combination the supply and appliance decision rules ("Services Framework"; appendix 1.6). The details of each decision rule and their implementation are shown in Appendix 1. An in-depth discussion of the relative merits of the respective approaches is presented in section 3 of the paper, and is based on applying the alternative decision rules and frameworks to assessing electricity access in Bangladeshi households using primary field data.
Differences in tier assignment based on applying different frameworks and algorithms were tested with the help of the Wilcoxon signed-rank test. This is a nonparametric test allowing for ordinal variables and not assuming normality in the data [Snedecor and Cochran, 1989]. It can compare two sets of scores that come from the same participant. The change variable in this case is simply the alternating algorithm/ framework used to compute the respective scores. It further assumes that paired observations are independent, which is affirmative (see appendix 5). Its modification, the signtest, further tests for the quality of matched pairs of observations. Furthermore, the correlation of tier scores with income is also tested (see appendix 11). As the assumptions for the Pearson Product-Moment Correlation could not be met (e.g. variable of ordinal scale, no outliers), the Spearman correlation coefficient, as a nonparametric measure, is computed to determine this relationship [Spearman, 1904].

3. Analysis and Discussion of Results

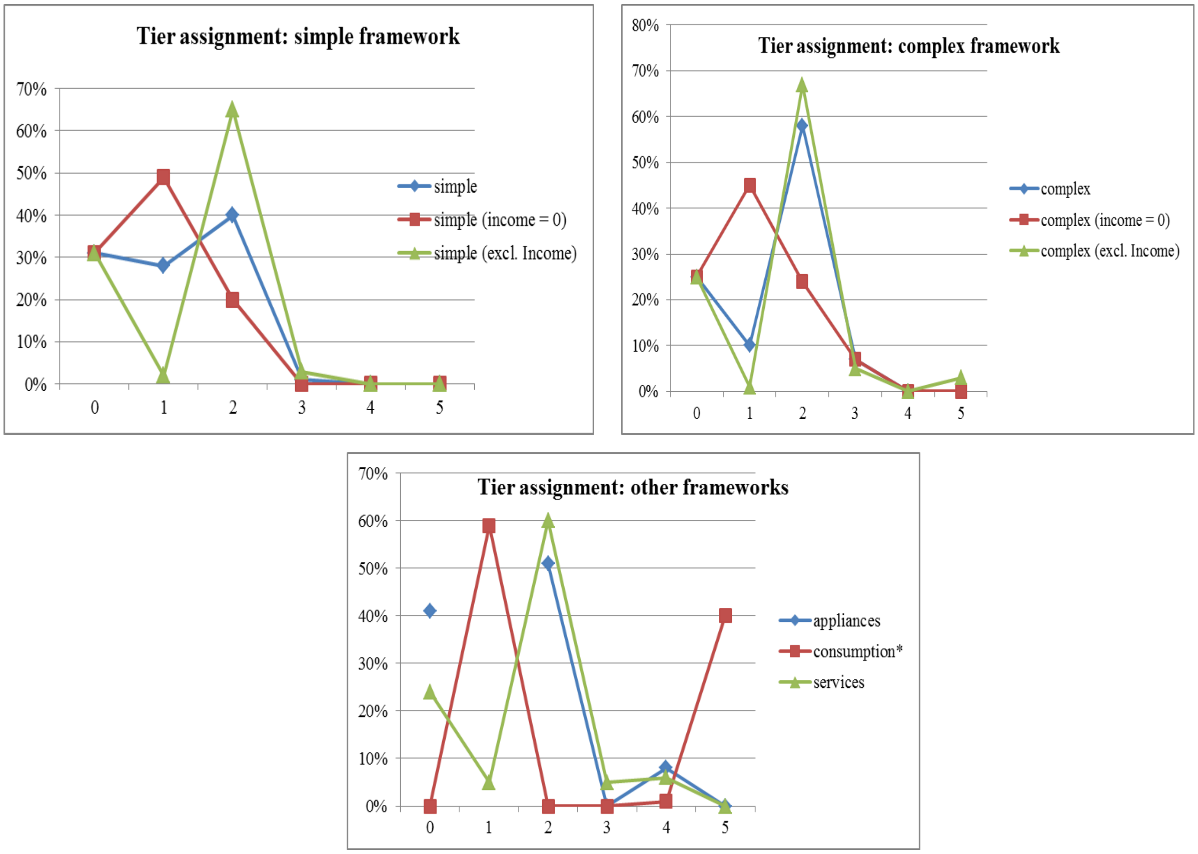
3.1 Sample tier performance: Descriptive statistics

Starting off from a macro picture, official statistics report that 43% of Bangladesh's rural population has access to the national grid, suggesting that 57% are energy or, at least, electricity poor [WBI, 2010]. Income poverty is estimated to be lower, at 35%. These statistics are approximately in line with the estimations based on the minimum end-use energy indicator, according to which 58% of the population is energy poor[8] and 45% income poor [Barnes et al. 2011]. In rural areas one can expect energy poverty to be higher than income poverty as physical access to modern energy infrastructure and supply is more of a constraint. Figure 2 showcases the sample based macro results applying the tier framework. It is clear that the multi-faceted and multi-tier nature of energy access is better captured by this approach than a binary approach. But as discussed hereafter, very quickly the complexity of data needs, differing algorithms and frameworks applied can result in restricting the simplicity, applicability and transparency of the approach. Differing frameworks and decision algorithms result in very different assessments of the electricity access situation in Bangladesh.

Almost the entire sample can be assigned to tier levels 0, 1 and 2 based on the simple version of the electricity supply algorithm, whereas applying the complex algorithm suggests a higher share being assigned to tier 2, and even a portion assigned to tier 3 (8%). High sensitivities towards the affordability criterion emerge when setting the income variable to 0 (a large share of tier 2 households drop down to tier 1) and when leaving income completely out of the equation (almost the entire sample of households shifts from tier 1 to tier 2 as a critical binding criteria is removed). It is interesting to note that the sample behaves almost exactly the same using the complex algorithm despite its higher flexibility in terms of tier assignment compared to the simple version, according to which households are simply assigned to the lowest performing tier). As the coding explains in appendix 1.2, affordability remains a critical factor also under the complex algorithm. Applying the appliances framework, a few households even get assigned a level of tier 4. Among others, equal shares remain between tiers 0-2. Electricity consumption data, as not adequately measured nor normally distributed, does not justify further interpretation.

[8] Basic minimum energy consists here of energy needed for a minimum quantity of lightning, cooking, and heating, whereas this paper is focused on services based on electricity. One can expect a high correlation of people depending on biomass and lacking access to the national grid. The former number, however, is usually found to be higher.

Figure 2: Multi-tier Measurement of Access to Electricity[9]



[#] based on max. capacity numbers instead of actual consumption, which is acceptable for SHS, but inadequate for the case of on-grid households..

Mean tier assignment values of each algorithm can be interpreted as the index value of energy access and the results are as follows:

Table 2: Tier based sample distribution

Variable	Obs	Mean	Std. Dev.	Min	Max
supply_simple	231	1.13	.88	0	4
supply_simple_inc0	231	.91	.75	0	4
supply_simple_no_inc	231	1.40	.97	0	4
supply_complex	231	1.48	.95	0	3
supply_complex_inc0	231	1.13	.86	0	3
supply_complex_no_inc	231	1.10	.85	0	3
appliances	166	1.54	1.02	.5	4
consumption	167	2.64	1.96	1	5
services	222	1.62	1.08	0	4

The electricity service framework, with the most degrees of freedom embedded in its algorithm, exhibits the most diverse distribution (highest standard deviation, except for consumption) and also the highest average tier assignment (see table 2). The higher value of the electricity appliance index than the two versions of the supply index is contrary to expectations as evidenced by the statement made by the IEA/WB that “electricity services [appliances] typically lag behind improvements in supply” [IEA/ WB, 2014, p. 52]. Still, closer

[9] Please note that a different affordability criterion has been used here, and is described in appendix 5 and discussed in Section 3.3.

scrutiny of statistical difference shows a different picture. The complex algorithm produces significantly different and higher results than the electricity appliance tier measurement (at the 1% level). This means that despite a higher mean, triggered by individual high differences in tier results of the service tiers, in depth analysis of the paired differences reveals that supply is, in fact, even ‘further ahead’ of appliances.

Appendix 5.1 shows an overview table of the test results on the equality of matched pairs applying the different frameworks. In several cases, the complex algorithm allows a higher tier assignment resulting in a significantly higher tier average at the 1% level. Electricity appliances as well as the consumption framework exhibit some outliers, which are discussed in Section 3.3. The combined framework of supply and appliances results in significantly higher (at 1% level) tier assignment than all the other frameworks used (except for the insignificant results on the consumption framework, and the complex version without considering income). This is mainly due to its increased flexibility in measurement among the individual attributes, where a poor performance in terms of low capacity can be compensated by a good performance in terms of used appliances. This is a strong result in favor of the combined framework as it suggests a better reflection of the multi-faceted status of energy poverty along with an adequate evaluation of modern energy technology interventions.

The stratified sample of households included in this study contains 46% with SHS, 30% with national grid access and 26% with no option for electricity. The tier assignment for different electricity generation sources exhibits an exclusive assignment to tier 0 for those without any form of primary energy source[10] (see appendix 6). 98% of the SHS users are assigned to either tier 1 or 2. A fairly diverse set of assignments is obtained from using the simple supply algorithm for grid-connected households ranging from tier 0 (16 observations) to tier 4 (1 observation). The latter result clearly showcases the limitations of the binary assessment of physical grid access.

Table 3 further shows that SHS users perform better, when there is a higher degree of flexibility in the underlying algorithm, as is evidenced by significantly higher tier 2 assignments when applying the complex version as compared to the simple version of the supply framework, and an even more pronounced result in the case of applying the service framework. It is even more striking that, on average, on-grid households get assigned to lower tiers than households with SHS, when applying the simple supply framework, because of their poor performance on the duration attribute (and because the lowest attribute performance determines the overall household tier assignment according to this framework). This is not the case for the complex or the service framework. The fact still remains, however, that on average on-grid households tier assignment is at a maximum (in the case of applying the service framework) at an index level of 2.49.

Table 3: Electricity Source and Tier Assignment

SHS tier perfomance

tier	Obs	Mean	Std. Dev.	Min	Max
simple_access	107	1.56	.54	0	2
complex_access	107	1.80	.40	1	2
services	107	1.91	.29	1	2

on-grid tier perfomance

tier	Obs	Mean	Std. Dev.	Min	Max
simple_access	69	1.28	.89	0	4
complex_access	69	2.04	.53	0	3
services	65	2.49	.83	1	4

3.2 Gap Analysis along the seven attributes for the case of Bangladesh

Neither the simple or complex algorithm for assigning an access tier to assess access to electricity supply is able to accurately capture the details of individual indicator/attribute results – so complementing the overall tier result with the full array of results for individual indictors/attributes is essential. Appendix 7 provides

[10] Except for one case in the services framework, which is assigned to tier 1.

further insights on the performance of the households along the seven attributes of the electricity supply framework as previously shown in figure 1.1. These results are estimated for a smaller sample. The smaller sample is a consequence of various skipping patterns applied in the questionnaire.[11] The analysis applies the decision rules as described in appendix 1.

In terms of *capacity*, a detailed analysis is undermined by the fact that the gradation variable in question A.02 was not sufficiently distinguished. The great majority of observations fall into the range of 51W-500W. For future research, it is therefore recommended to have an intermediate option of 200W included.[12]

The *duration* of supply out of 24h, seems to be less of an issue as the majority of the households (about 90%) fall into the range of having at least 8h of electricity supply per day. Evening supply, in contrast, seems to be far more relevant, as almost 20% have less than 2h of supply and about 43% state they have exactly 2h of evening supply. The grid seems to have capacity problems, especially at peak load times, which in the case of Bangladesh is in the evening [BPDP, 2015]. It should be noted though that data reliability may differ among the two questions. An estimation of evening supply seems to be easier than estimating the amount of hours over an entire day. Additionally, in the sample households, electricity is mostly used in the evening hours, so the question regarding hours of supply in the evening is always likely to be easier to respond to for the respondents, provided that evening hours are clearly defined as is the case in the questionnaire used. In terms of *reliability,* 69% of the households suffer from more than three interruptions per week, and about 93% of the households undergo regular outages, stating these last more than half an hour. On the *quality* dimension, 19% of the people with a connection to the national grid report appliance breakage due to voltage drops.

Affordability is measured here based on relative electricity expenditure, as it is considered adverse if a high share of income is spent on it [Bazilian et al. 2010]. Table 4 below summarizes the results.

Table 4: Average relative electricity expenditure for the sample

Electricity Expenditure/ Total Income	**Sample share**
average	6%
nothing	17%
less than 5%	64%
5% - 10%	17%
more than 10%	19%

As can be seen, 19% of the interviewed households end up spending more than 10% of their total income for electricity, which would result in them being assigned to the tier 1 level or below. It should be noted that electricity expenditure is highly dependent on quality and quantity of services received and therefore being a single metric needs to be interpreted carefully.

Concerning *legality,* there is not a single household officially stating that it is not paying electricity bills. On the other hand, only 61 households state they have a meter, whereas 69 are considered grid connected. There seems to be a good tracking of the electricity users affiliated to the PBS scheme. Furthermore, all SHS users indicate they pay their bill to the respective partnering organization of the IDCOL program, making legality a minor issue in the present context.

Health & Safety is only reflected in the productive use section of the questionnaire, and thus only received 34 responses from the microbusinesses in the dataset. Based on this data, it seems a negligible factor, as only one unit states an incidence in the past. In a nutshell, the gap analysis suggests that health & safety, as well as legality seem to be less of an issue. Affordability, in turn, measured here as energy expenditure as a share of

[11] The skipping pattern is based on the household's primary electricity source. Many questions apply only to households connected to the national grid. Whereas this is useful for some of the questions in order to keep the questionnaire time short, the authors recommend not following the skipping pattern for many decentralized options in order to get a better tier based evaluation of these types of energy interventions. Please refer to appendix 4, Q.A01 to review the exact skipping pattern.

[12] Update: The latest version of the framework does exhibit an intermediate level of 150W now (appendix 1.7).

income,[13] seems to be of potential concern and is discussed in greater detail in the subsequent subchapter. *Reliability* and *quality* only affect the ability to reach at least a tier 3 level. Here, for the on-grid customers, a better load management and transformer improvement may have the potential to move up to 93% of the on-grid households (under the simple algorithm) to a higher tier level, provided that the second most pressing issue of evening hour supply is also tackled. A more detailed analysis of these issues is needed, however.

3.3 SHS financing in Bangladesh

If we are to rely on existing statistics that consider income poverty to be far less than energy poverty [WBI, 2010; Barnes et al. 2011], the unaffordability incidence of 19% , as measured in this sample, is fairly high. People with access to the grid spend on average 3%, people with SHS 8%, and ‘completely off-grid’ people 7% of their total income on electricity services, as reflected in the questionnaire (appendix 8.1).[14] Even though these results require careful interpretation, especially due to the fact that SHS follow an ownership model, whereas grid access follows a service model, it seems fair to say that the end-user cost of the widely adopted SHS scheme appears too high. Appendix 8.2 shows the average cost for a SHS is 3.5 times higher than kerosene and 1.4 times that for equivalent service from the national grid. This strongly contradicts the widely cited claim that the SHS financing schemes work, as the monthly payment installments set off the current kerosene expenditures, among others for households [Mondal, 2010; Chakrabarty and Islam, 2011; Komatsu et al. 2011]. The savings potential of kerosene seems to be overstated in literature. Here, Blunck [2007] concludes that when considering that a maximum of 80% of the total kerosene consumption is actually replaced, SHS in fact do not amortize in a timeframe over 20 years. The data used in that study is based on 2006 prices, and major changes have occurred since then with significantly declining solar PV prices, rising kerosene prizes, and higher efficiency appliances entering the market, which is likely to have moved the calculation more in favor of the SHS program [Khan, 2015]. The present study’s results however, indicate SHS owners, on average, spend twice as much of their income on the system, as compared to people using kerosene as their primary source of lighting that have a similar level of income to people connected to the national grid (appendix 8.3). Rahman and Ahmad [2013] came to similar conclusions referring to SHS as often merely adding to a household’s ‘social status’. It needs to be carefully noted though that the service options of a SHS, in the given sample range of up to 85Wp, allow for a range of advanced appliances, such as color TV (22 in the sample). This service stands in no comparison to what kerosene can provide. Still, the average expenditure for a 20Wp system is Tk. 380 (still twice as much as that for kerosene). Nonetheless, a SHS is at an advantage in terms of cost per lumen hour output, as well as in the reduced indoor smoke, among other factors [Groh, 2014]. These welfare improvements, however, are not household budget effective in the short term. Therefore, it would be interesting to see the international community adopt a revised version of the candidate framework in order to design smart subsidies conditioned on specific tier improvements. This can facilitate a cost-benefit analysis of pro-poor interventions with respect to both short term monetary and non-monetary impacts, always provided the respective tier framework adequately reflects all dimensions mentioned above.

A preliminary result of this study is that the market seems to lack an electricity package that lifts people at least to tier 1, which is accessible and more affordable than the current portfolio of SHS. Brossmann [2013] draws similar conclusions in his comparative impact assessment of (small) SHS in Bangladesh. Affordability also needs to be improved for the present SHS program in order for more SHS users to reach a tier 2 or tier 3 level. Given, however, that the main SHS expenditures[15] are bound to the credit tenure as it represents an investment, paid-up SHS owners may move automatically up the tier scale as the affordability criterion in that case will no longer apply to them.

3.4 Specific recommendations regarding attribute measurement, tier frameworks and assignment algorithms

This part of the analysis is dedicated to an evaluation of the underlying decision rules as well as differences and sensitivities of applying different algorithms across the respective frameworks. It is important to note that the majority of the decision rules do not apply for SHS and solar lantern interventions, but only for national grid, mini-grid and diesel generators due to the skipping pattern suggested in the underlying questionnaire for some of the questions. It is strongly recommended to not apply the skipping pattern, and also collect data on

[13] Appendix 1 – figure 1 showcases the application of a different criterion than the 5% and 10% thresholds of relative energy expenditure, which is discussed later.

[14] Note that these statistics suffer from a lot of noise, and standard deviations are extremely high.

[15] Also after the credit period still maintenance cost will incur, mainly battery replacement cost etc., but to a much lesser extent.

capacity, duration, quality and reliability for all types of systems. In the present dataset this has only been done for a minority of the SHS owners (8%). Nevertheless, a lot can be learned from the little data. Most attributes for electricity supply measurement do capture key elements of supply. However, specific additional recommendations are discussed in what follows.

3.4.1 Rethinking the capacity attribute in light of new appliance efficiencies evident in the market

The simple algorithm undermines the SE4ALL goal of energy efficiency. With higher efficiency appliances[16], a lower demand and storage capacity is needed to provide the same duration of service supply. Higher efficiency can lead to lower energy consumption. Appendix 1.5, as an example, evaluates the implications of applying the consumption framework on the present SHS program in Bangladesh as well as on the up-coming IFC solar lantern program under the Lighting Bangladesh initiative [IFC, 2015]. As a matter of fact, the products that fall under this program (<= 5Wp), do not even reach the tier 1 level based on the consumption framework, or the capacity attribute as applied in the updated supply framework[17]. The products falling under the much acclaimed Bangladeshi IDCOL SHS program (usually <= 75Wp), also fail to attain a performance higher than tier 1. Based on an apparent trade-off between energy efficiency and energy consumption, one finds a paradox that applying the present frameworks, a better energy service may result in a lower tier ranking. Using the simple algorithm, a lower score in peak capacity, would rule out a higher possible overall tier score supported by sufficient daily and evening supply hours in connection with a good performance in electricity appliances available. This line of argument finds support by Craine et al. 2014 (see appendix 9) and has further implications for the investments estimated for achieving universal energy access by 2030, done by the IEA. Pachauri et al. (2013) estimate that globally, US$$_{2005}$ 65–86 billion per year would be required to achieve near universal access to electricity and clean cooking by 2030 (US$$_{2005}$ 10.7-15.2 billion per year for rural electrification alone). They also state, however, that taking into consideration feasible decentralized options, investments are likely to be lower compared to their estimates that assumes all access is achieved via grid extension alone. Craine et al. (2014) argue that the investment estimations could potentially decline from a level of USD 32 billion per year over the next 20 years to as low as USD 10 billion per year, largely as a result of revised efficiency values for decentralized energy options. This, in turn, has been heavily criticized by Trembath [2014] as being far too low. The importance of including the latest trends in energy efficient appliances remains, however, undisputed. The suggested service framework is a first step to overcome this problem. However, as shown in appendix 1.4, the appliance framework still assumes certain Wattages for household appliances /e.g. TV 31-150W) and determines the capacity requirements accordingly. These do not reflect latest market developments in appliance efficiencies.

3.4.2 Re-designing the affordability attribute

As much as the new tier framework wants to capture the multiple dimensions of energy poverty, it loses part of its power if the simplified decision rule is applied that recommends to always choose the lowest performing attribute as the final tier score. This explains to a large extent why, as already stated, the simple tier score is significantly lower than the score estimated when using the complex algorithm (1% level) or the service framework, which provides much higher degrees of flexibility (1 % level). The scores on the affordability attribute drive the results for the tier assignment. However, the affordability indicator does not accurately capture affordability constraints faced by households. Neither the upfront nature or lumpiness of costs is easily measured by the recommended indicator, nor are the costs (discounted) associated with appliances needed to convert electric supply into useful service, included in this indicator. Comparing kWh prizes for electricity ignoring quantity used (e.g. standard consumption package of 365kWh per annum or 1kWh per day needs to be less than 10% of household income) results in a misleading framework.

It is further recommended to add another layer to the affordability attribute, namely flexibility in repayment accounting for the poor's cash flow constrains. Collins et al. (2010) explain the complexities of the portfolios of the poor that require an array of sophisticated methods to sooth various liquidity traps. Pay-As-You-Go (PAYG) solutions have revolutionized the SHS market in East Africa allowing its customers increased flexibility in their payment plans both in terms of up-front payment as well as amount and frequency of monthly installments [Moreno & Bareisaite, 2015]. This in some cases even leads to payments far ahead of

[16] E.g.: There are 15‘‘color LED DC TVs presently in the market that consume about 6W and DC brushless ceiling fans consuming approx. 5W, the best LED lights have a ratio of 120lm/W. If I have all of those appliances running 4h a day, this makes 56Wh (for two lights). This is by far lower than the required 200Wh for tier 2.

[17] The updated supply framework requires a minimum of 20Wh for tier 1 assignment and 274Wh for tier 2, in contrast to 4Wh and 200Wh, respectively, in an earlier version that was applied here.

the plan making sure the available income is not spent otherwise. These technology innovations, that are expected to be implemented soon in Bangladesh, among other countries, need to be reflected in the tier framework. This could be done through a flexibility indicator feeding into the affordability attribute, as greater flexibility in repayments can substantially improve a household's medium term cash-flow management. Consequently, affordability ought no longer to be defined merely as an indicator reflecting relative share of electricity expenditure (either for consumption packages, or kWh, or lumen hours), but should also reflect the degree of payment flexibility as a service improvement [Moreno & Bareisaite, 2015]. Again, these innovations, especially in the early market phase, are more costly. Without a tier framework reflecting their added value, a cost-benefit-analysis remains very difficult. At the end of the day, it should be the goal of such a framework to get closer to allowing a comparative analysis of what an hour of TV, light or fan costs to a household instead of comparing peak capacities and kWh prices, by always taking into consideration economies of scale.

3.4.3 (Ir-) relevance of the electricity consumption framework

If electricity supply performance is high in the tier assignment, but there are extremely low values on consumption, the reasons behind this can be manifold. There may not be an ability to pay, there may not be the need for bigger amounts (possibly due to un-availability of appliances or availability of an appliance of higher efficiency than expected) etc. But aren't all these reasons already reflected in the attribute of the supply and the appliances framework? And if so, why is an additional consumption framework needed, especially if its values coincide with the daily capacity value already included in the access framework. If daily capacity is limited, which is the case for most off-grid interventions; it may very well be interpreted as a higher boundary condition on consumption. In the case of a centralized generation and storage facility (e.g. national grid) this is not the case, at least if it is computed in a simplistic manner as is done in appendix 1.5. But here the question remains, what additional information do higher or lower consumption values give us really for measuring energy access, which are not already reflected in one of the access attributes or in the appliance framework? Furthermore, the implication of applying the consumption framework in its current form, for attaining energy efficiency goals, is at the very least questionable.

3.4.4 Further refinement of attributes

The following recommendations are based on the latest version of the multi-tier framework (appendix 1.7). Applying the attributes related to peak capacity and daily hours undermine efficiency goals as service output is not measured. To take the example of light, output is measured in lumen. Efficacy is measured by lumen output per Watt. While the performance of CFLs remains relatively stable, LEDs improve by a factor of 8-15, when applying this criterion, leading to drastically reduced cost for the same, which in turn might suggest better affordability [Jacobson, 2015]. The present framework, however, does not measure service output, so a high energy consuming light bulb (less efficient) drives up consumption, possibly leading to a higher tier assignment, but may give the same hours of light in the evening with less luminosity. Hence, this can only be fixed by a combined evaluation of single metrics (in this case cost per lumen hour output). In terms of the duration attribute, it is advised that a finer refinement could bring about better results, especially for the evaluation of off-grid solar applications. Here, a further distinction in the tier decision rule is recommended to distinguish between tier 1, 2 and 3, for e.g. to establish a minimum of 3h for tier 3. The reliability, quality and legality attribute can be easily expanded to lower tiers as well in order to reflect the performance of specific energy interventions in the off-grid sector in a better way. Regarding the health attribute, the integration for household use is strongly recommended in order to take adverse health effects of kerosene lighting into account, but in addition also the health implications of lead acid batteries in the case of SHS where proper recycling facilities are absent or often the recycling process is not enforced.

3.4.5 Comparison of tier assignments based on differing algorithms and frameworks

Neither of the tier assignment algorithms – simple or complex – to measure electricity supply is ideal and results in very different assessments of access. These, in turn, differ from the tier assignments that result from applying the other alternative frameworks. However, it seems clear from the analysis that a higher degree of flexibility, reflected through an algorithm that evaluates combinations of attributes or even frameworks, provides a more nuanced measure of energy poverty, especially as it has the ability to better reflect energy interventions in the off-grid sector. At the same time, however, the complex algorithm is more prone to errors, as it is more complicated to calculate, which may undermine the approach's simplicity, applicability and transparency. The suggested service framework shares this shortcoming as it merges the conditions of the complex access framework with the ones from the appliances framework. It takes the list of appliances that cause tripping or are recommended not to be used from the appliance framework, modifying the rule in a way that it says that these appliances are usable without causing any form of tripping. This transforms it into a positive statement and allows households with limited generation capacity, but sufficient access to 'higher tier' appliances, to be assigned to a higher overall tier performance (appendix 1.6). In the earlier version of the complex algorithm, appliances were also integrated but in a rather confusing manner. As reflected in Q. B3 of the questionnaire (see appendix 4), which asks for problems related to certain appliances along with their availability. The elicitation of this information caused confusion among the respondents. Further improvements are needed here, however, could only partially be applied in the suggested service framework algorithm as underlying data for computation is based on the earlier version of the questionnaire. Concerning the algorithms itself, the criterion on allowed appliances to a certain extent undermines the tier performance rating of SHS in the given case, as the POs only allow a very limited selection of appliances to be used with their systems (see appendix 10). This happens mainly due to concerns regarding warranty claims on the battery. Furthermore, the complex algorithm contains a default condition that limits a unit with a SHS to perform no better than tier 2, and that with a minigrid no better than tier 3. Both conditions should be abondoned for future use.

Lastly, appendix 11 shows the Spearman correlation coefficients for all modifications of the different frameworks and how they relate to household income, which is presumably the most difficult indicator to measure reliably. The appliance framework does not show any significant correlation with income, whereas the simple and complex supply algorithm of the access framework as well as the service framework are positively correlated with income (1% significance level). Here the higher average tier value that results from applying the complex algorithm (0.41) over the simple rule (0.26) stands out. These results confirm the outcome of the sensitivity analysis (Section 3.1, figure 2), that reveal that excluding income from the decision rules or setting its level to 0, results in a much higher/ lower tier performance, reflected in a major shift of households being assigned to tier 1 to tier 2 and vice versa. It also suggests that the complex algorithm places more value on income than the simple one, as it appears more often in its decision rules. The suggested service framework shows the same pattern here (0.41, 1% significance level), so is equally prone to income measurement errors. Further improvements are, therefore, needed. Nonetheless, appendix 12 also shows a considerable amount of data points with a fairly high income but a tier 0 assignment, which, in turn, suggests that affordability, is not necessarily the key decision factor, but rather one important element among several that manifest in a status of energy poverty.

4. Conclusions

The objective of any measurement framework must ultimately lie not in measuring the supply of energy/electricity, but rather whether this supply enables certain vital services (communication, illumination, thermal comfort, entertainment, etc.), which ultimately improve human wellbeing. However, measuring energy at the level of services is difficult. This is because it requires a measurement of much more than the energy carriers themselves (e.g. transformation and end-use equipment). The authors recommend revising the algorithms aiming at a compound algorithm that combines elements from the supply and the appliance framework analysis. First, this seems to be the most promising approximation in the absence of a direct measurement of energy services, by measuring energy at the useful level. Second, it reflects advances in energy efficiency. Third, it overcomes the shortcoming of a decision rule based on a single metric. At the same time, however, another layer of complexity to the algorithm in comparison to the simple version is added. A trade-off between "methodological sophistication and theoretical accuracy on the one hand, and applicability and transparency on the other" is unavoidable here [Bazilian et al. 2010, p. 17]. Recognizing the urgent need of a theoretical underpinning for the measurement of progress towards the first SE4ALL goal, this paper strongly advocates in favor of the multi-tier framework. It also values the need for pragmatism in light of the urgent need of an indicator that is fairly easily computable. Nonetheless, it concludes that the presently favored simple version of the algorithm for tier assignment does not give sufficient justice to the multi-faceted and multi-tiered nature of energy access, especially in the current times of rapid technology innovation (e.g. DC appliance efficiency; PAYG business models). The paper, therefore, recommends the algorithm can potentially be improved. Although there will always remain a trade-off between an approach that is more reflective of reality, but is fairly complex and hence prone to errors, and an approach that is simpler, easily computable, but also has several shortcomings. It should be noted though that the approaches discussed here require the same amount of data and that the debate in this paper is simply based on calculation methods and alternative algorithms. In light of a likely inclusion of energy access in the upcoming SDGs, the authors advocate for a fast review of the present method and a quick adoption in the field through systematic integration in existing surveys or, what might be quicker and more prudent, to put it high on the agenda of the multilateral national offices of the SE4ALL member countries.

As the new framework allows for a reflection of country specific energy interventions, this paper for the first time evaluates the widely acclaimed solar home system program of Bangladesh. Currently, SHS are not reflected at all in (inter-) national statistics on energy access. According to the multi-tier framework, the sample households with SHS score at the tier 1 and at best at the tier 2 levels, depending on the application of the capacity attribute. Based on the latter criterion, eligible products under up-coming programs such as the IFC Lighting Bangladesh program do not even qualify for a tier 1 assignment. A major challenge, despite opposing rhetoric, remains the issue of affordability, including higher flexibility in repayment plans. Monthly installments of the microcredit based scheme are still too high compared to expenditures for kerosene and on-grid access, as well as in relation to total household income. The health and safety attribute seem to be neglected in the household case and needs to be better integrated, by also including a measure of hazardous waste exposure (e.g. lead acid batteries) and respective recycling procedures. The latest trends in energy efficient appliances that are already available locally, however, are presently paving the way for higher tier performances provided a more sophisticated tier assessment algorithm, as suggested herein, is adopted. There is also a need for actions that address households at lower income levels, as present schemes address largely higher income rural customers. It should be carefully noted that the tier assignments are highly sensitive to parameter changes, different algorithms, and data requirements. The performance evaluation of country specific energy interventions can differ significantly, depending on the type of algorithm that is used, which may lead to conflicts when it comes to building consensus for a universal measurement framework among the SE4ALL member countries. Once this is achieved, pro-poor policies that influence energy access by enabling households to achieve higher tier levels can be designed and implemented more effectively. Still, only what gets measured, also gets done, so immediate action is needed here.

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Appendix

1. Tier Algorithms

* codes in this section are based on the attached questionnaire but also interpreted below

*1.1 Algorithm Electricity Supply I (simple version)**

Tier 0:
A01=8 OR A02=1 OR A06<4 OR A07<2

Tier 1:
Tier 0=FALSE AND (A06<8 OR A02=2 OR MONTHLY_INSTALLM>10%INCOME)

Tier 2:
Tier 0=FALSE AND Tier 1=FALSE AND (A02=3 OR A05=1 OR A08>21 OR A14=4,5,6,7)

Tier 3:
Tier 0=FALSE AND Tier 1=FALSE AND Tier 2=FALSE AND (A06<16 OR A07<4 OR A02=4 OR A08>7)

Tier 4:
Tier 0=FALSE AND Tier 1=FALSE AND Tier 2=FALSE AND Tier3=FALSE AND (A06<23 OR A08>3 OR A09>2)

Tier 5:
Tier 0=FALSE AND Tier 1=FALSE AND Tier 2=FALSE AND Tier3=FALSE AND Tier 4=FALSE

1.2 Algorithm elelctricity supply II (complex version)

Tier 0: (A01=7) OR (A01=8) OR (A02=1) OR (A06>4) OR A07<2)

Tier 1: (Tier 0=FALSE) AND [(A02=2) OR (B.3=H) OR (B.3=I) OR (A01=6) OR ((A11=NO) AND ((A01=1) OR (A01=2) OR (A01=4) OR (A01=6)) AND (0.8<=10*A13)) OR ((A11=NO) AND (A01=3) AND (0.8<=10*PL)) OR ((A11=YES) AND (0.8<=10*PT))]

Tier 2: (Tier 0=FALSE) AND (Tier 1=FALSE) AND [(A02=3) OR (B.3=K,L,M,N,U,Q,S) OR (A01=4,6) OR (A06<8) OR (A14=4,5,6,7) OR (25=YES)]

Tier 3: (Tier 0=FALSE) AND (Tier 1=FALSE) AND (Tier 2=FALSE) AND [(A02=4) OR (B.3=O,P,V,T,W,X,Y) OR (A01=2,3) OR (A06<16) OR (A07<4) OR ((A11=NO= AND (A01=3) AND (0.8<20*PL)) OR ((A11=NO) AND 0.8<20*(A13)) OR ((A11=YES) AND (0.8<20*PT)) OR (AO8>3) OR (A09>31)]

Tier 4: (Tier 0=FALSE) AND (Tier 1=FALSE) AND (Tier 2=FALSE) AND (Tier 3=FALSE) AND (A08<=3) AND (A09<31) AND (A06<=22)

Tier 5: (Tier 0=FALSE) AND (Tier 1=FALSE) AND (Tier 2=FALSE) AND (Tier 3=FALSE) AND (Tier 4=FALSE) AND (A08<3) AND (A09<31) AND (A06>22)

Verbal interpretation:
Tier 0: A household has no access to electricity or uses dry cell batteries as its main source, or it has less than 1W of capacity or less than 4h of electricity supply per day, or less than 2h per night.

Tier 1: A household that does not fall under the category of tier 0 and with a capacity between 1W-50W or a colored TV or fan that causes tripping or is not allowed to be used. A household that has a solar lantern as primary source or an illegal connection. Or a household that has access to a minigrid, a SHSor rechargable batteries as main source of electricity in combination with elelctricity expenditure higher or equal than 10% of the household’s total income. Or a household with an unmetered access to a diesel generator where the diesel expenditure is more than 10% of its total income or a metered access to the grid where the monthly tariff is equal or higher than 10% of its total income.

Tier 2: A household that does not fall under the category of tier 0 or 1 with a total capacity between 51W and 500W or a printer, air cooler electric food processor, rice cooker, fridge, toaster or electric hari dryer that causes tripping or is not allowed to be used. Or the household has access to SHS or a rechargable battery system or less than 8h of electricity supply per day or pays his bill for the grid to a private person or doesn’t pay at all. Or the household has experienced damages due to voltage drops.

Tier 3: A household that does not fall under the category of tier 0, 1 or 2 that has a capacity between 501W and 2000W. Or a washing maschine, water pump, water heater, microwave oven, air conditioner, elelctric space heater or elelctric cooling system causes tripping or is not allowed to be used. Or the household has access to a mingrid or a diesel generator as primary source or there is less than 16h of electricity a day, or less than 4h in the evening. Or there is no meter and the household is connected to a diesel generator with a cost higher than 5% of the household’s total income (obsolete condition). Or there is a (un-)metered electricity access which costs more than 5% of the household’s total income. Or there are more than 3 unpredictable interruptions per week staying on longer than 31min.

Tier 4: A household that does not fall under the category of tier 0, 1, 2 or 3 that has three or less unpredictable interrruptions per week which last less than half an hour and 22h or less of electricity supply per week.

Tier 5: A household that does not fall under the category of tier 0, 1, 2, 3 or 4 that has three or less unpredictable interrruptions per week which last less than half an hour and more than 22h of ellectricity supply per week.

Challenges & Suggestions:

- Mix of attributes is more complicated to calculate and therefore more prone to errors;
  - ➔ precise manuals have to be developed with pre-formatted formulas.

- Tier 3 has an obsolete criterion (diesel generator);
  - ➔ Should be deleted.

- There is a default condition in tier 2 that inhibits a SHS to perform better than tier 2, and in tier 3 for a minigrid;
  - ➔ Should both be deleted.

- The condition of appliances that caused tripping in the past or are not allowed to be used for level 1,2 and 3 is confusing for the respondent and undermines SHS performance with higher efficiencies appliances;
  - ➔ change it and instead integrate the elelctricity service algorithm at the same spots with the combined that the respective appliances (as defined in the appliance algortihm, not as above) do not cause tripping.

1.3 Algorithm Electricity Appliances

Tier 0/1: (Tier 2 = FALSE) AND (Tier 3 = FALSE) AND (Tier 4 = FALSE) AND (Tier 5 = FALSE) AND (B1=A) OR (B1=B) OR (B1=C) OR (B1=D) AND (B1 = E) OR (B1 =F)

Tier 2: (Tier 0/1 = TRUE) AND (B1=I) AND (B1=G) OR (B1=H) OR (B1=J) OR (B1=K) AND (Tier 3 = FALSE) AND (Tier 4 = FALSE) AND (Tier 5 = FALSE)

Tier 3: (Tier 2 = TRUE) AND (B1=L) OR (B1=M) OR (B1=N) OR (B1=O) AND (Tier 4 = FALSE) AND (Tier 5 = FALSE)

Tier 4: (Tier 3 = TRUE) AND (B1=P) OR (B1=Q) OR (B1=R) OR (B1=S) OR (B1=T) OR (B1=U) OR (B1=V) AND (Tier 5 = FALSE)

Tier 5: (Tier 4 = TRUE) AND (B1=W) OR B1=X) OR B1=Y)

Verbal interpretation:
Tier 0/1: A household uses either an incandescent light, fluorescent tube, CFL or LED and has a radio or a phone charger.

Tier 2: A household complies with Tier 0/1 and has an electric fan and a BW, color TV, computer or a printer.

Tier 3: A household complies with Tier 2 and has an air cooler, elelctric food processsor, rice cooker, or a washing machine.

Tier 4: A household complies with Tier 3 and has a water pump, refrigerator, elelctric iron, elelctric hair dryer, microwave, elelctric toaster or water heater.

Tier 5: A household complies with Tier 4 and has an air conditioner, electric space heater or a dish washer.

Challenges & Suggestions:

- Tier 0 and 1 are not disitnguished
  - ➔ Distinguish tier 0 and tier 1[18]
  - ➔ adjusted algorithm

[18] Has already been implemented in the upgraded version.

Tier 0: (Tier 1 = FALSE) AND (Tier 2 = FALSE) AND (Tier 3 = FALSE) AND (Tier 4 = FALSE) AND (Tier 5 = FALSE)

Tier 1: (Tier 0 = TRUE) AND (B1=A) OR (B1=B) OR (B1=C) OR (B1=D) AND (B1 = E) OR (B1 =F)

- The improvement from a incandescent light, fluorescent tube or CFL light to LED lights is not reflected;

➔ Include LED technolgoy as an improvement step to tier 1;

- Change the appliance list for tier 3 and 4;

➔ refrigerators and water pumps should be assigned to tier 3 instead of 4, as they can be run with relatively small decentralized solar systems (max 150Wp consumption), where as the washing machine could easily go to tier 4;

- So far, the tier framework for electricity appliances runs in parallel to the one capturing the supply;

➔ Aim for an integration of the service rule into the supply algorithm.

1.4 Summary matrix of the multi-tier framework: household electricity appliances

		Tier-0	Tier-1	Tier-2	Tier-3	Tier-4	Tier-5
Tiers	**Tier Criteria**	-	Task Lighting **AND** Phone Charging	General Lighting **AND** Television **AND** Fan (if needed)	Tier-2 **AND** Any Medium Power Appliances	Tier-3 **AND** Any High Power Appliances	Tier-2 **AND** Any Very High Power Appliances
Applications	**Type of Appliances**	-	Very low power appliances (<30W)	Low power appliances (31-150W)	Medium power appliances (151-600W)	High power appliances (600-1500W)	Very high power appliances (>1500W)
	Indicative List of Appliances	**Tier-0**	**Tier-1**	**Tier-2**	**Tier-3**	**Tier-4**	**Tier-5**
	Lighting	-	Task lighting	Multi-point general lighting			
	Entertainment & Communication	-	Phone charging, Radio	Television, Computer, Printer			
	Space Cooling & Heating	-		Fan	Air cooler		Air conditioner*, Space heater*
	Refrigeration	-			Refrigerator*, Freezer*		
	Mechanical Loads	-			Food processor, Washing m/c, Water pump		
	Product Heating	-				Iron, Hair dryer	Water heater
	Cooking	-			Rice cooker	Toaster, Microwave	Electric cooking

1.5 Summary matrix of the multi-tier framework: household electricity consumption

		Tier-0	Tier-1	Tier-2	Tier-3	Tier-4	Tier-5
	Annual Consumption levels (KWh)	< 7	≥ 7	≥ 100	≥ 365	≥ 1250	≥ 3000
	Daily Consumption levels (Wh)	< 20	≥ 20	≥ 274	≥ 1000	≥ 3425	≥ 8219

Implications for (pico) Solar Home System tier performance rating[19]

peak capacity (Wh) = generation capacity (Wp) * supply hours (peak sun hr) * derate factor

panel size (Wp)	**derate**	**peak sun hrs**	**peak capacity (Wh)**	**highest possible tier assignment**
2.5	0.63	4.5	7	0
5	0.63	4.5	14	0
10	0.63	4.5	**28**	**1**
20	0.63	4.5	57	1
30	0.63	4.5	85	1
40	0.63	4.5	113	1
50	0.63	4.5	142	1
75	0.63	4.5	213	1
100	0.63	4.5	**284**	**2**
120	0.63	4.5	340	2
200	0.63	4.5	567	2
375	0.63	4.5	**1,063**	**3**

* assumed values for the Bangladeshi context as discussed in Groh et al. 2015

1.6 Algorithm combined elelctricity services framework

Variables:

Tier 5 (Supply) = T5Su
Tier 4 (Supply) = T4Su
Tier 3 (Supply) = T3Su
Tier 2 (Supply) = T2Su
Tier 1 (Supply) = T1Su
Tier 0 (Supply) = T0Su

Tier 5 (Appliances) =T5Ap
Tier 4 (Appliances) = T4Ap
Tier 3 (Appliances) = T3Ap
Tier 2 (Appliances) =T2Ap
Tier 1 or 0 (Appliances) = T01Ap

Tier 0: (Tier 5 = FALSE) AND (Tier 4 = FALSE) AND (Tier 3 = FALSE) AND (Tier 2 = FALSE) AND (Tier 1 = FALSE) AND (T0Su = TRUE) OR ((T01Ap = FALSE) AND (T0Su = TRUE))

Tier 1: (Tier 5 = FALSE) AND (Tier 4 = FALSE) AND (Tier 3 = FALSE) AND (Tier 2 = FALSE) AND ((T01Ap = TRUE) AND (T0Su = FALSE)) OR (T1Su = TRUE)

Tier 2: (Tier 5 = FALSE) AND (Tier 4 = FALSE) AND (Tier 3 = FALSE) AND ((T2Ap = TRUE) OR (T2Su = TRUE))

Tier 3: (Tier 5 = FALSE) AND (Tier 4 = FALSE) AND ((T3Ap = TRUE) OR (T3Su = TRUE))

Tier 4: (Tier 5 = FALSE) AND ((T4Ap = TRUE) OR (T4Su = TRUE))

Tier 5: (T5Ap = TRUE) OR (T5Su = TRUE)

[19] Note the following tables are subject to maximum capacity not consumption, which, however, represents the maximum boundary condition for consumption.

1.7 Update electricity access framework

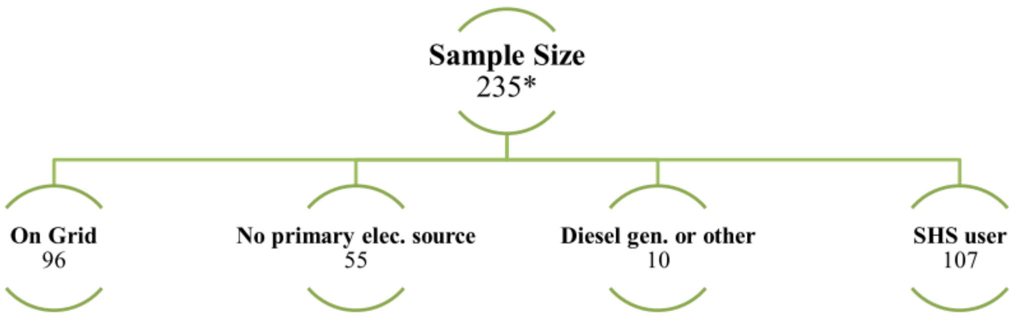
<table>
<tr><th></th><th colspan="2"></th><th>Tier-0</th><th>Tier-1</th><th>Tier-2</th><th>Tier-3</th><th>Tier-4</th><th>Tier-5</th></tr>
<tr><td rowspan="9">Attributes</td><td rowspan="2">1. Peak capacity</td><td>Power</td><td rowspan="2">-</td><td>V. Low Power Min 5 W</td><td>Low Power Min 70 W</td><td>Medium Power Min 200 W</td><td>High power Min 800 W</td><td>V.High Power Min 2 kW</td></tr>
<tr><td>Daily capacity</td><td>Min 20 Wh</td><td>Min 274 Wh</td><td>Min 1.0 KWh</td><td>Min 3.4 KWh</td><td>Min 8.2 KWh</td></tr>
<tr><td rowspan="2">2. Duration</td><td>Hours per day</td><td>-</td><td colspan="2">Min 4 hrs</td><td>Min 8 hrs</td><td>Min 16 hrs</td><td>Min 23 hrs</td></tr>
<tr><td>Hours per evening</td><td>-</td><td colspan="2">Min 2 hrs</td><td>Min 2 hrs</td><td>Min 4 hrs</td><td>Min 4 hrs</td></tr>
<tr><td colspan="2">3. Reliability</td><td colspan="3">-</td><td>Max 21 disruptions per week (Max 3 disruptions per day)</td><td>Max 7 disruptions per week</td><td>Max 3 disruptions per week of total duration < 2 hours</td></tr>
<tr><td colspan="2">4. Quality</td><td colspan="3">-</td><td colspan="3">Voltage problems do not prevent the use of desired appliances</td></tr>
<tr><td colspan="2">5. Affordability</td><td colspan="3">-</td><td colspan="3">Cost of a standard consumption package of 365 kWh per annum is less than 5% of household income</td></tr>
<tr><td colspan="2">6. Legality</td><td colspan="3">-</td><td colspan="3">Bill for Grid Electricity is paid to the utility / pre-paid card seller / authorized representative</td></tr>
<tr><td colspan="2">7. Health and Safety</td><td colspan="3">-</td><td colspan="3">Absence of past accidents and perception of high risk in the future</td></tr>
</table>

2. Administrative Map of Bangladesh

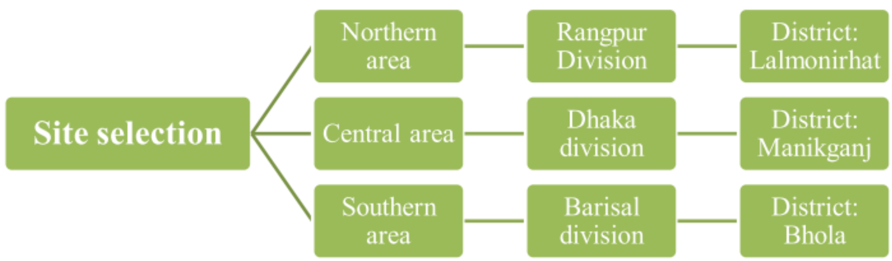
Source: Swedish South Asian Studies Network - Lund University: http://www.sasnet.lu.se/news-sources/bangladesh-map

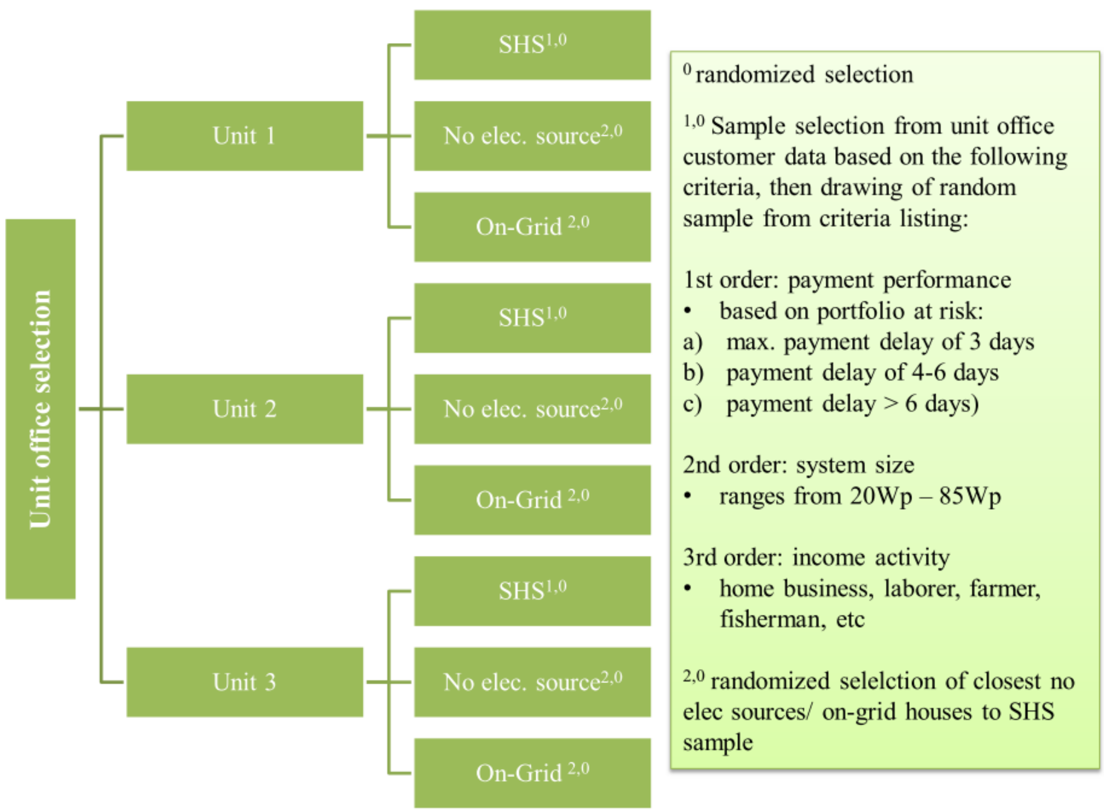
★ indicates selected districts (distance from Dhaka): Lalmonirhat (343km), Manikganj(63km) and Bhola (205km).

3. Sample Selection



* 10 (5%) of respondents reported multiple primary energy sources





4. Multi-tier framework questionnaire: Bangladesh

- supplementary appendix

5. Statistics of tier differences

5.1 Test for equality of matched pairs for different frameworks and algorithms

Testing procedures

Paired t-test

Underlying assumptions:

- ✓ variables are matched pairs
- ➔ same households/ microbusinesses are matched
- ✓ no significant outliers in the differences
- ➔ as variables are ordinal (scaled from 0-5), there are no severe outliers
- ✓ underlying distribution is approxamitely normal
- ➔ not fulfilled
- ✓ variable are continous
- ➔ not fullfilled

Shapiro-Wilk W test for normal data

Variable	Obs	W	V	z	Prob>z
supply_simple	231	0.96	6.6	4.4	0.00001
supply_simple_inc0	231	0.96	6.1	4.2	0.00001
supply_simple_no_inc	231	0.92	13.6	6.0	0.00000
supply_complex	231	0.95	7.7	4.7	0.00000
supply_complex_inc0	231	0.99	1.5	1.0	**0.15701**
supply_complex_no_inc	231	0.95	8.4	4.9	**0.09203**
appliances	168	0.97	3.4	2.8	0.00265
consumption	167	0.99	0.7	-0.8	**0.78935**
services	222	0.98	3.3	2.7	0.00000

Wilcoxon signed-rank test

Framework	Algorithm	Sensitivity	Tier Assignment						Test for equality of matched pairs				
			0	1	2	3	4	5	supply (simple)	supply (complex)	appliances	consumption	services
Electricity Supply	simple	-	31%	28%	40%	1%	0%	0%	-	bigger***	smaller**	bigger***	bigger***
		income = 0	31%	48%	20%	0%	0%	0%	bigger***	bigger***	bigger***	bigger***	bigger***
		excl. income	32%	2%	66%	3%	0%	0%	smaller***	bigger	bigger	bigger**	bigger***
	complex	-	25%	10%	58%	7%	0%	0%	smaller***	-	smaller***	bigger	bigger***
		income = 0	25%	45%	24%	6%	0%	0%	bigger	bigger***	bigger**	bigger***	bigger***
		excl. income	25%	1%	68%	5%	0%	0%	bigger	bigger***	bigger***	bigger***	bigger
Electricity Appliances	-	-	41%		51%	0	8%	0	bigger**	bigger***	-	bigger***	bigger***
Electricity Consumption#	-	-	42%	-	-	-	1%	72%	smaller***	smaller	smaller***	-	bigger**
Electricity Services	combined	-	-	5%	58%	4%	6%	-	smaller***	smaller***	smaller***	smaller**	-

*	10%
**	5%
***	1%
#	based on max. capacity numbers instead of actual consumption which is acceptable for SHS, but inadequate for the case of on-grid households

6. Elelctricity source and tier assignment

No electricity/ nothing: supply_simple vs. supply_complex algorithm

supply_sim ple	supply_complex 0	Total
0	55	55
Total	55	55

Solar Home System: supply_simple vs. supply_complex algorithm

supply_sim ple	supply_complex 1	2	Total
0	0	2	2
1	8	35	43
2	13	49	62
Total	21	86	107

National Grid: suply_simple vs. supply_complex algorithm

lsupply_sim ple	supply_complex 0	1	2	3	Total
0	2	0	12	2	16
1	0	2	14	5	21
2	0	0	30	0	30
3	0	0	0	1	1
4	0	0	0	1	1
Total	2	2	56	9	69

No electricity/ nothing: supply_complex algorithm vs. services framework

complex_su pply_tier	services_tier 0	1	Total
0	54	1	55
Total	54	1	55

Solar Home Systems: supply_complex algorithm vs. services framework

complex_su pply_tier	services_tier 1	2	Total
1	10	11	21
2	0	86	86
Total	10	97	107

National Grid: supply_complex algorithm vs. services framework

complex_supply_tier	services_tier 1	2	3	4	Total
0	0	1	0	1	2
1	1	1	0	0	2
2	0	42	0	10	52
3	0	0	7	2	9
Total	1	44	7	13	65

7. Attributes of electricty service supply – gap analysis

Capacity Wattage

equipment wattage	Freq.	Percent	Cum.
<1W	2	3.17	3.17
1W-50W	2	3.17	6.35
51W-500W	52	82.54	88.89
501W-2000W	5	7.94	96.83
>2000W	2	3.17	100.00
Total	63	100.00	

Duration out of 24h

duration of daily supply	Freq.	Percent	Cum.
2	2	2.82	2.82
5	2	2.82	5.63
6	1	1.41	7.04
7	2	2.82	9.86
8	4	5.63	15.49
9	3	4.23	19.72
10	4	5.63	25.35
12	12	16.90	42.25
13	4	5.63	47.89
14	5	7.04	54.93
14.5	1	1.41	56.34
15	1	1.41	57.75
16	4	5.63	63.38
16.5	1	1.41	64.79
17	3	4.23	69.01
18	7	9.86	78.87
18.5	1	1.41	80.28
19	5	7.04	87.32
20	5	7.04	94.37
21	1	1.41	95.77
22	2	2.82	98.59
24	1	1.41	100.00
Total	71	100.00	

Duration Evening Supply

duration of evening supply	Freq.	Percent	Cum.
0	2	2.78	2.78

```
          1 |         12       16.67       19.44
          2 |         31       43.06       62.50
          3 |         23       31.94       94.44
          4 |          4        5.56      100.00
------------+-----------------------------------
      Total |         72      100.00
```

Reliability

```
Interruptio |
    ns/week |      Freq.     Percent        Cum.
------------+-----------------------------------
          0 |          8       11.76       11.76
          3 |          1        1.47       13.24
        5.5 |          1        1.47       14.71
          6 |          1        1.47       16.18
          7 |          2        2.94       19.12
          9 |          2        2.94       22.06
         10 |          6        8.82       30.88
         11 |          1        1.47       32.35
         12 |          3        4.41       36.76
         13 |          1        1.47       38.24
         14 |          8       11.76       50.00
         15 |          2        2.94       52.94
         16 |          1        1.47       54.41
         18 |          2        2.94       57.35
         20 |          8       11.76       69.12
         21 |          3        4.41       73.53
         24 |          1        1.47       75.00
         25 |          2        2.94       77.94
         28 |          2        2.94       80.88
         30 |          9       13.24       94.12
         35 |          1        1.47       95.59
         60 |          1        1.47       97.06
         80 |          2        2.94      100.00
------------+-----------------------------------
      Total |         68      100.00

duration of |
    outages |      Freq.     Percent        Cum.
------------+-----------------------------------
          0 |          4        6.35        6.35
         .5 |          1        1.59        7.94
          1 |         15       23.81       31.75
       1.17 |          2        3.17       34.92
       1.25 |          1        1.59       36.51
        1.5 |         12       19.05       55.56
          2 |         17       26.98       82.54
          3 |          3        4.76       87.30
          4 |          1        1.59       88.89
        8.5 |          1        1.59       90.48
         10 |          3        4.76       95.24
         12 |          1        1.59       96.83
      12.08 |          1        1.59       98.41
         16 |          1        1.59      100.00
------------+-----------------------------------
      Total |         63      100.00
```

Quality

```
  damage of |
 appliances |
    occured |      Freq.     Percent        Cum.
------------+-----------------------------------
```

	Freq.	Percent	Cum.
No	55	80.88	80.88
Yes	13	19.12	100.00
Total	68	100.00	

Affordability

Variable	*Obs*	*Mean*	*Std. Dev.*	*Min*	*Max*
affordabil~y	*223*	*.0596704*	*.07724*	*0*	*.47*

Legality

electricity meter	*Freq.*	*Percent*	*Cum.*
No	*3*	*4.55*	*4.55*
Yes	*63*	*95.45*	*100.00*
Total	*66*	*100.00*	

Health and Safety

biz_health_ issues	Freq.	Percent	Cum.
0	33	97.06	97.06
1	1	2.94	100.00
Total	34	100.00	

8. Expenditure and Affordability for different electricity sources

8.1 Affordability

Variable	Obs	Mean	Std. Dev.	Min	Max
exp_kerose~p	91	192.46	157.09	35	1035
exp_nation~d	21	480.24	255.52	110	1000
exp_solarh~m	95	668.93	278.36	288	1301

8.2 Expenditure

National grid

Variable	Obs	Mean	Std. Dev.	Min	Max
affordabil~y	65	.031	.07	0	.32

Solar Home System

Variable	Obs	Mean	Std. Dev.	Min	Max
affordabil~y	104	.075	.069	0	.33

No electricity/ nothing

Variable	Obs	Mean	Std. Dev.	Min	Max
affordabil~y	54	.065	.087	.00	.47

8.3 Accumulated Income

National Grid

Variable	Obs	Mean	Std. Dev.	Min	Max
acc_income	68	17260.59	13715.66	0	69000

Solar Home System

Variable	Obs	Mean	Std. Dev.	Min	Max
acc_income	107	15530.56	12834.63	0	72000

Kerosene

Variable	Obs	Mean	Std. Dev.	Min	Max
acc_income	55	8643.64	5752.38	0	30000

9. Tier definitions under an energy effiicent scenario

TABLE 1 - CLEAN ENERGY FOR ALL END USE MODEL

	Business as Usual						Energy Efficient					
	Tier 0	**Tier 1**	**Tier 2**	**Tier 3**	**Tier 4**	**Tier 5**	**Tier 0**	**Tier 1**	**Tier 2**	**Tier 3**	**Tier 4**	**Tier 5**
Service description	Kerosene lamps, candles, etc	Task lighting and phone charging (OR radio)	General lighting AND television AND fan (if needed)	Tier 2 AND any low power applicances	Tier 3 AND any medium power applicances	Tier 3 AND any high power applicances	Kerosene lamps, candles, etc	Task lighting and phone charging (OR radio)	General lighting AND television AND fan (if needed)	Tier 2 AND any low power appliances	Tier 3 AND any medium power appliances	Tier 3 AND any high power appliances
Peak available capacity (W)	-	2.5	50	200	2000	2000	-	2.5	25	125	1500	3500
Duration (hours/day)	-	> 4	> 4	> 8	> 16	> 22	-	> 4	> 4	> 8	> 16	> 22
Number of lamps	2	2	4	4	8	8	2	2	4	4	8	8
Lamp technology	Kero	Bulb	Bulb	Bulb	Bulb/halogen	Bulb/halogen	Kero	LED	LED	LED	LED	LED
Watts/lamp	-	15	40	40	60	60	-	1	1	3	5	5
Lumens		150	500	500	750	750		150	500	500	750	750
Hours/day	4	4	4	4	4	4	4	4	4	4	4	4
Phone charger, max mA		500	500	800	800	800		500	500	800	800	800
Number of phone chargers		1	1	2	2	2		1	1	2	2	2
Fan or air-con (watts)			4	30	50	1300			2	15	25	1000
TV (watts)			20	80	200	200			10	20	100	100
Refrigerator, capacity cu.ft				<5	5-15	>15				<5	5-15	>15
Refrigerator (W)				160	240	360				80	120	180
Referigerator, hours on				6	10	12				6	10	12
Washing machine capacity, cu.ft					<4.5 cu.ft	>4.5 cu.ft					<4.5 cu.ft	>4.5 cu.ft
Washing machine (W)					1500	2000					750	1200
kWh/year - lighting		44	234	234	701	701		3	18	18	58	58
kWh/year - phone charging		3	3	8	8	8		3	3	8	8	8
kWh/year - fan or air-con		7	49	82	82	1460		3	15	27	27	1095
kWh/year - TV		0	29	117	292	292		0	15	58	146	146
kWh/year - refrigeration		0	0	350	876	1577		0	0	175	438	788
kWh/year - washing machine		0	0	0	219	292		0	0	0	110	146
kWh/year - other		0	0	0	0	219		0	0	0	0	219
Energy consumption, kWh/year		**53**	**315**	**791**	**2178**	**4549**		**9**	**50**	**287**	**788**	**2461**
							% reduction	83%	84%	64%	64%	46%

Source: Craine et al., 2014

10. Table 1: RSF Load Allowance criteria for SHS

SL No	Package	Package Description (panel - battery size)	Allowed Load Type	No of loads	Approx. Watt Consumption
1	10Wp SHS	10Wp - 15AH	LED Tube Light	2 X LED Tube Light	6
2	20Wp SHS	20Wp - 23AH	LED Tube Light	3 X LED Tube Light	9
3	20Wp SHS	20Wp - 30AH	LED Tube Light	3 X LED Tube Light	11
4	30Wp SHS	30Wp - 30AH	LED Tube Light, 15" TV	2 X LED Tube Light, 1 X 15" TV	26
5	40Wp SHS	40Wp - 45AH	LED Tube Light, 15" TV	3 X LED Tube Light, 1 X 15" TV	29
6	45Wp SHS	45Wp - 45AH	LED Tube Light, 15" TV	3 X LED Tube Light, 1 X 15" TV	31
7	50Wp SHS	50Wp - 55AH	LED Tube Light, 15" TV	4 X LED Tube Light, 1 X 15" TV	34
8	65Wp SHS	65Wp - 71AH	LED Tube Light, 15" TV	5 X LED Tube Light, 1 X 15" TV	39
9	75Wp SHS	75Wp - 80AH	LED Tube Light, 15" TV & Fan	6 X LED Tube Light, 1 X 15" TV, 1 X Fan	44
10	85Wp SHS	85Wp - 85AH	LED Tube Light, 15" TV & Fan	7 X LED Tube Light, 1 X 15" TV, 1 X Fan	67

Source: RSF, 2015

11. Spearman correlations between tier algorithm and income

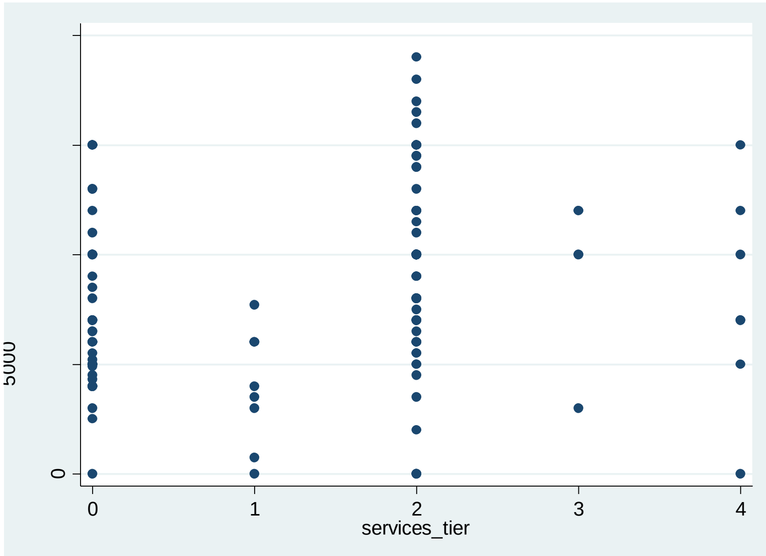
Assumptions:
1. variable ordinal or continuous scale
 elec_supl_simple_tier - ordinal
 elec_supl_complex_tier - ordinal
 elec_ appliance_tier - ordinal
 acc_income - continuous

2. monotonic relationship
fairly-monotonic, spearman not very sensitive to outliers

```
spearman simple_supply_tier acc_income

Number of obs =     230
Spearman's rho =       0.2579

Test of Ho: simple_supply_tier and acc_income are independent
    Prob > |t| =       0.0001

spearman complex_supply_tier acc_income

Number of obs =     230
Spearman's rho =       0.4145

Test of Ho: complex_supply_tier and acc_income are independent
    Prob > |t| =       0.0000


spearman elec_ appliance_tier acc_income

Number of obs =     165
Spearman's rho =       0.0777

Test of Ho: elec_appliance_tier and acc_income are independent
    Prob > |t| =       0.3209


spearman  services_tier acc_income

Number of obs =     221
Spearman's rho =       0.4147

Test of Ho: services_tier and acc_income are independent
    Prob > |t| =       0.0000
```

32

12. Scatter plot service tier assignment versus accumulate income (< BDT 20,000)



13. Supplementary Appendix

Multi-tier framework questionnaire: Bangladesh

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Multi-tier Framework Questionnaire: Bangladesh

INTRODUCTION AND GENERAL INFORMATION

"Hello, my name is ________________. We are conducting a survey on behalf of the United International University. This survey is part of a study aimed to measure the access to electricity in Bangladesh. We would like to ask you few questions which will take about 20min. All the answers that you provide will be kept anonymous– only members of the survey team will have access to this information. You can stop the interview at any time, ask me to clarify any question, or ask me to repeat something if you don't understand. Your cooperation is greatly appreciated."

HOUSEHOLD IDENTIFICATION

		CODE	NAME
1.	REGION[1]	[ ][ ]	____________________
2.	UPOZILLA[2]	[ ][ ]	____________________
3.	VILLAGE	[ ][ ]	____________________
4.	WARD #	[ ][ ]	
5.	UNION PARISHAD		____________________
	LOCALITY	URBAN....1 RURAL....2 PERI-URBAN....3	[ ]
7.	NAME OF HOUSEHOLD HEAD:		____________________
8.	HOUSEHOLD HEAD PHONE NUMBER:	[ ][ ][ ][ ][ ][ ][ ][ ][ ][ ]	

GPS COORDINATES OF THE DWELLING:

9. [___|___] ° [___|___] . [___|___|___] 'N

10. LONGITUDE (E)

[___|___] ° [___|___] . [___|___|___] 'E

Special notes:

[1] MA = Manikgnaj; BH = Bhola; LA = lalmonirhath

[2] RA= Razibpur; TE = Tepra; JH = Jhitka |MO = Monpura; DU = Dularhat Charfashion; TA = Tajumuddin | HA = Hatibandha; KA = Kaliganj Lamonirhat; PA = Patgram

INTERVIEW DETAILS

11.	ENUMERATOR ID:	☐☐	12.	ENUMERATOR NAME:	________
13.	DATE OF INTERVIEW [DD/MM/YY]	☐☐ / ☐☐ / ☐☐			
14.	TIME INTERVIEW STARTED:	:	15	TIME INTERVIEW ENDED:	:

Multi-tier Framework Questionnaire: Bangladesh

MODULE 0: CHARACTERISTICS OF HOUSEHOLD MEMBERS

0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	Please state the names of people who currently live in the household, starting with the head of the household.	Is [NAME] a male or female? **1. MALE** **2. FEMALE**	How old is [NAME]? (YEARS)	What is the highest level/grade of school that [NAME] has attended? **[for age 3 and above only] (ENTER 0 FOR NO SCHOOLING)** 1 NURSERY 2 PRIMARY 3 POST-PRIMARY 4 SECONDARY 5 HIGHER SEC. 6 UNDERGRAD 7 POSTGRAD	What is [NAME]'s current main occupation? (FOR MEMBERS AGES 16-65) 1 FARMER 2 TRANSPORT 3 FISHERMAN/FISHMONGER 4 SKILLED TRADE (CARPENTRTRY 5 MASONRY, WEAVER, ELECTRICIA 6 REPAIR WORK) 7 BARBER, TAILOR, LAUNDRY 8 HAWKER 9 DOMESTIC HELP 10 UNEMPLOYED 11 HOMES BUSINESS 12 STUDENT 13 NRB 14 OTHER (SPECIFY)	What is [NAME]'s current main employment status 1 WAGE EMPLOYMENT (not including casual day labor) 2 NON-FARM SELF EMPLOYMENT (EMPLOYER) 3 NON-FARM SELD EMPLOYMENT (OWN-ACCOUNT WORKER) 4 NON-FARM SELF-EMPLOYMENT (UNPAID FAMILY WORKER) 5 FAMILY FARMING 6 CASUAL DAY LABORER 7 UNPAID INTERNSHIP 8 NOT ENGAGED IN ECONOMIC ACTIVITY 9 OTHER (SPECIFY)	What is [NAME] average monthly income?	Is [NAME] a business owner or self-employed/ freelancer in the area?
			Year	Level			Amount in Tk. per month	yes/ no
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								

3

Multi-tier Framework Questionnaire: Bangladesh

MODULE A: ACCESS TO ELECTRICITY SUPPLY

SOURCE & CAPACITY			
A. 01	What is the primary source of electricity in the household? ***If answer is 4-5-6 please ask the number of devices in the household***	☐ 1. National grid connection from [*name of utility*]→**A.02** ☐ 2. Local mini-grid **(Specify source)** →**A.02** ________________________ ☐ 3. Fossil fuel based generator →**A.02** ☐ 4. Solar home system → **A.13** 4aHow many? (……………) ☐ 5. Solar lantern → **A.13** 5a How many? (………………)	☐ 6. Rechargeable battery system (e.g. car battery) →**A.02** 6a How many? (………………) ☐ 7. Dry cell battery (Non-rechargeable) →**AB.01** ☐ 8. No electricity →**AB.01** ☐ 9. Other **(specify)**: ________________________
A. 02	(Question based on observation: Read the value from the nameplate of the electricity supply equipment or ask for the equipment documentation)	☐ 1. Less than 1 Watt ☐ 2. 1 Watt – 50 Watts ☐ 3. 51 Watts – 500 Watts	☐ 4. 501 Watts – 2000 Watts ☐ 5. More than 2000 Watts ☐ 99. No documentation
SEASONALITY			
A. 03	In the last 3 months, did the number of outages of your primary source of electricity vary across seasons?	☐ 1. Yes ☐ 2. No →**A.06 [ask all questions based on the last 3 months]**	
A. 04	If yes, which is the most difficult season for electricity performance in your household? Please respond to following questions considering the worst season of the year **[ask all next questions based on the worst season]**	☐ 1. Season 1 (month specification) ☐ 2. Season 2 (month specification)	☐ 3. Season 3 (month specification) ☐ 4. Season 4 (month specification)
QUALITY OF SUPPLY			
A. 05	[During the worst season/in the last 3 months] Have any appliances been damaged by electricity supply?	☐ 1. Yes ☐ 2. No	
DURATION OF SUPPLY			
A. 06	[During the worst season/in the last 3 months] On average, how many hours of electricity do you receive from your primary source ***each day*** (per 24 hours)?	☐☐ [hours] (max 24 hours)	
A. 07	[During the worst season/in the last 3 months] On average, how many hours of electricity do you receive **in the evening, from 6 pm to 10 pm** from your primary source each day?	☐☐ [hours] (max 4 hours) **(check consistency: number of hours cannot be higher than A.07)**	
RELIABILITY OF SUPPLY			
A. 08	[During the worst season/in the last 3 months] On average, how many times do you face unpredictable interruptions of your primary source of electricity per week? (Note: **unscheduled interruptions** are unanticipated disruption when the user would expected the supply to be available)	☐☐ [number of interruptions per week] **[insert 00 if none]**	
A. 09	[During the worst season/in the last 3 months] On average, how long is **each** unpredictable interruption of your primary source of electricity?	☐☐ [hours] ☐☐ [minutes]	
A.10	At what time of the day do these interruptions normally occur?	(see table below)	
AFFORDABILITY			
A. 11	Does your household have a meter for the primary source of electricity?	☐ 1. Yes ☐ 2. No	
A. 12	In the last 3 months, how much did you spend for your primary source of electricity on average per month?	☐☐☐☐ [Tk.]	
A. 13	What is the price you currently pay:	***If Question A.01 is 1. Grid connection or 2. Local mini-grid*** ☐ by Kwh ☐☐☐ [Tk.] | ☐ fixed charged ☐☐☐ [Tk.]	

A.10 time table:

	6am-10am	10am-2pm	2pm-6pm	6pm-10pm	10pm - 2am	2am-6am
scheduled						
unscheduled						

		If Question A.01 is 3. Fossil fuel based generator ☐ by litre of fuel ☐☐☐ [Tk.] | ☐ fixed charged ☐☐☐ [Tk.]	
		If Question A.01 is 6. Rechargeable battery system ☐ to recharge the battery one time ☐☐☐ [currency]	
		If Question A.01 is 4. Solar home system 5. Solar lantern ☐ monthly instalment for the electricity supply equipment ☐☐☐ [Tk.]	
LEGALITY OF CONNECTION			
A. 14	Who do you currently pay for your primary source of electricity?	☐ 1. Local representative/official of the electricity company ☐ 2. Pre-paid meter card seller ☐ 3. Community /village/ municipality ☐ 4. Relative ☐ 5. Neighbour	☐ 6. Land lord ☐ 7. No one ☐ 8. No need to pay **–I have already paid for the equipment** ☐ 9. PO ☐ 10. Others (specify): ______________________________

Multi-tier Framework Questionnaire: Bangladesh

ADDITIONAL QUESTIONS		
A.15	Overall, are you satisfied with the primary source of electricity in your household?	☐ 1. Yes ☐ 2. No
A.16	Does your primary source of electricity cover all your needs?	☐ 1. Yes → **B.01** ☐ 2. No
A.17	If not, which of the following aspects of the primary source of electricity would you like to improve? [Rank according to priority from 1- 7]	☐ Longer supply hours ☐ More appliances I can use ☐ Lower cost ☐ More flexible payment ☐ Address low voltage issues and voltage fluctuations ☐ Reducing number of unpredictable interruptions ☐ Reducing duration of unpredictable interruptions
A.18	What do you use when you face problems with your electricity supply? (only if grid)	☐ 1. Invertors ☐ 2. Voltage stabilizer ☐ 3. Generators ☐ 4. Battery and storage devices ☐ 5. Others (specify): ___________________________
A.19	Would you like to change your primary source of electricity?	☐ 1. Yes ☐ 2. No
A.20	If so, which source would be your main preference?	☐ 1. National grid connection ☐ 2. Local mini-grid **(Specify source)**__________________________ ☐ 3. Fossil fuel based generator ☐ 4. Solar home system ☐ 5. Solar lantern ☐ 6. Other: _________________

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Multi-tier Framework Questionnaire: Bangladesh

MODULE B: ACCESS TO ELECTRICITY SERVICES

B.1 When do you most use these appliances? [Please mark with a cross, compare A03 for appliances in use]

	Appliance	Quantity	Hours of operation per day	6am-10am	10am-2pm	2pm-6pm	6pm-10pm	10pm -2am	2am-6am
A	Incandescent Light Bulbs								
B	Fluorescent Tube								
C	CFL								
D	LED								
E	Radio								
F	Phone charger								
G	Black and white TV								
H	Colour TV								
I	Electric Fan								
J	Computer								
K	Printer								
L	Air Cooler								
M	Electric Food Processor								
N	Rice Cooker								
O	Washing Machine								
P	Water Pump								
Q	Refrigerator								
R	Electric Iron								
S	Electric Hair Dryer								
T	Microwave Oven								
U	Electric Toaster								
V	Water Heater								
W	Air Conditioner								
X	Electric Space Heater								
Y	Electric cooking system								
Z.1	Dish Washer								
Z.2	OTHER								
Z.3	…								

B.2 Do you use your appliances always at those times the most?

- ☐ Yes, always
- ☐ No, only during the week, specify: ___________________________
- ☐ No, depends on the season: specify: ___________________________
- ☐ Other: ___________________________

B.3 In the last 3 months, has any appliance caused tripping OR have you been advised not to use any appliance with your primary source of electricity?

	Appliance
A	Incandescent Light Bulbs
B	Fluorescent Tube
C	CFL
D	LED
E	Radio

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Multi-tier Framework Questionnaire: Bangladesh

F	Phone charger
G	Black and white TV
H	Colour TV
I	Electric Fan
J	Computer
K	Printer
L	Air Cooler
M	Electric Food Processor
N	Rice Cooker
O	Washing Machine
P	Water Pump
Q	Refrigerator
R	Electric Iron
S	Electric Hair Dryer
T	Microwave Oven
U	Electric Toaster
V	Water Heater
W	Air Conditioner
X	Electric Space Heater
Y	Electric cooking system
Z.1	Dish Washer
Z.2	OTHER
Z.3	…

MODULE AB: SOURCES OF LIGHTING USED WITHIN THE HOUSEHOLD

(All households should respond)

ENERGY SOURCES FOR LIGHTING					
	AB	AB.01	AB.02	AB.03	AB.04
Type of lighting source	Does the household use this energy source for lighting?	How many lamps/bulbs do you use? [number]	What is the frequency of use?	On average, how much do you spend per month for each lighting **fuel**? [currency]	On average, what quantity of fuel to do use each month?
a. Candle	☐ 1. Yes ☐ 2. No		☐ Every day or almost ☐ Few times per week ☐ Few times per month ☐ Few times per year	☐☐☐☐	☐☐ candles
b. Kerosene lamp	☐ 1. Yes ☐ 2. No	☐☐	☐ Every day or almost ☐ Few times per week ☐ Few times per month ☐ Few times per year	☐☐☐☐	☐☐ liters
c. Diesel/gasoline lamp	☐ 1. Yes ☐ 2. No	☐☐	☐ Every day or almost ☐ Few times per week ☐ Few times per month ☐ Few times per year	☐☐☐☐	☐☐ liters
d. LPG lamp	☐ 1. Yes ☐ 2. No	☐☐	☐ Every day or almost ☐ Few times per week ☐ Few times per month ☐ Few times per year	☐☐☐☐	☐☐ cylinders
e. Biogas lamp	☐ 1. Yes ☐ 2. No	☐☐	☐ Every day or almost ☐ Few times per week ☐ Few times per month ☐ Few times per year	☐☐☐☐	
f. Dry-cell battery torch	☐ 1. Yes ☐ 2. No	☐☐	☐ Every day or almost ☐ Few times per week ☐ Few times per month ☐ Few times per year	☐☐☐☐	☐☐ batteries
g. Rechargeable battery (e.g. car battery)	☐ 1. Yes ☐ 2. No	☐☐	☐ Every day or almost ☐ Few times per week ☐ Few times per month ☐ Few times per year	☐☐☐☐	☐☐ recharges
h. solar lantern	☐ 1. Yes ☐ 2. No	☐☐	☐ Every day or almost ☐ Few times per week ☐ Few times per month ☐ Few times per year	☐☐☐☐	
i. solar home system	☐ 1. Yes ☐ 2. No	☐☐	☐ Every day or almost ☐ Few times per week ☐ Few times per month ☐ Few times per year	☐☐☐☐	
j. mini-grid	☐ 1. Yes ☐ 2. No	☐☐	☐ Every day or almost ☐ Few times per week ☐ Few times per month ☐ Few times per year		
k. national grid	☐ 1. Yes ☐ 2. No	☐☐	☐ Every day or almost ☐ Few times per week ☐ Few times per month ☐ Few times per year		
l. Others (specify) ________________	☐ 1. Yes ☐ 2. No	☐☐	☐ Every day or almost ☐ Few times per week ☐ Few times per month ☐ Few times per year	☐☐☐☐	☐☐ [unit]

Multi-tier Framework Questionnaire: Bangladesh

MODULE AC: SOLAR BASED LIGHTING SYSTEMS

Only households that have responded yes to **AB.01.h** (solar lantern) and **AB.01.i** (solar home system); please ask for the installment plan/ documentation

QUALITY OF SUPPLY			
AC. 01	How many solar systems or devices do you currently use in the household?	☐☐ [number]	
PRIMARY SYSTEM (A)			
AC.02a	In this device, are the solar panel and the storage battery together or separate (connected by a wire)?	☐ 1. Together, in a single casing ☐ 2. Separate, connected by a wire ☐ 3. There is no storage battery	
AC. 03a	In this device, are the battery and the bulb together or separate?	☐ 1. At least one light bulb is separated from the battery by a wire ☐ 2. Light bulbs are together with the battery ☐ 3. This system or device does not power any lights ☐ 4. There is no storage battery	
AC.04a	In this device, how many light bulbs do you have?	☐ 1. One light bulb ☐ 2. Two light bulbs (that can be separated from each other) ☐ 3. Three (that can be separated from each other) ☐ 4. Four (that can be separated from each other) ☐ 5. Five or more light bulbs (that can be separated from each other) ☐ .6 Zero – this system or device does not power lights	
AC. 05a	What type of light bulbs do you use?	☐ 1. LED ☐ 2. CFL ☐ 3. Incandescent ☐ 4. Other (Specify) __________________	
AC.06a	What is the size of the solar module [centimetres]	☐☐☐x ☐☐☐	
AC. 07a	What is the power rating of the solar module? [watts peak]	☐☐☐	
AC.08a	Please identify the device using the photos provided Name: PO	_________________	
AC. 09a	How long do you expect this system to last before it needs repair or replacement?	☐☐ months	
AC. 10a	On average how many hours do you use this system for lighting each day?	☐☐ hours	
AC.10b	At what times do you use the system most?	(see grid below)	

	6am-10am	10am-2pm	2pm-6pm	6pm-10pm	10pm -2am	2am-6am
Light						
Fan						
TV						
Mobile						

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Multi-tier Framework Questionnaire: Bangladesh

		Radio						
		…						
		….						

AC. 11a	How many people can use this device / system at the same time without moving the lamp around for task lighting (e.g. for reading or for cutting vegetables)? / Can all people use it	☐☐yes/ no
AC. 12a	Are you able to power mobile phones or other loads with this device?	☐ 1. Yes ☐ 2. No
SECONDARY SYSTEM (B)		
AC.02b	In this device, are the solar panel and the storage battery together or separate (connected by a wire)?	☐ 1. Together, in a single casing ☐ 2. Separate, connected by a wire ☐ 3. There is no storage battery
AC. 03b	In this device, are the battery and the bulb together or separate?	☐ 1. At least one light bulb is separated from the battery by a wire ☐ 2. Light bulbs are together with the battery ☐ 3. This system or device does not power any lights ☐ 4. There is no storage battery
AC.04b	In this device, how many light bulbs do you have?	☐ 1. One light bulb ☐ 2. Two light bulbs (that can be separated from each other) ☐ 3. Three or more light bulbs (that can be separated from each other) ☐ 4. Zero – this system or device does not power lights
AC. 05b	What type of light bulbs do you use?	☐ 1. LED ☐ 2. CFL ☐ 3. Incandescent ☐ 4. Other (Specify) __________________
AC.06b	What is the size of the solar module [centimetres]	☐☐☐ x ☐☐☐
AC. 07b	What is the power rating of the solar module? [watts peak]	☐☐☐
AC.08b	Please name the brand of the system	-------------------- ☐ Not identifiable
AC. 09b	How long do you expect this system to last before it needs repair or replacement?	☐☐ months
AC. 10c	How many hours do you use this system for lighting each day?	☐☐ hours
AC.10d	At what times do you use the system most?	

	6am-10am	10am-2pm	2pm-6pm	6pm-10pm	10pm -2am
Light					
Fan					
TV					
Mobile					
Radio					
…					
….					

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Multi-tier Framework Questionnaire: Bangladesh

AC. 11b	How many people can use this device / system at the same time without moving the lamp around for task lighting (e.g. for reading or for cutting vegetables)?	☐☐
AC. 12b	Are you able to power mobile phones or other loads?	☐ 1. Yes ☐ 2. No

Questions for all respondents

AC. 13	Are you able to recharge mobile phones within 500m from your house?	☐ 1. Yes ☐ 2. No
AC. 14	How many times per month do you recharge mobile phones outside the household?	☐☐
AC. 15	How much does a recharge cost?	☐☐ {Tk.}

Questions for RSF customers only

AC. 16	How many times have you faced a technical problem with the system within in the last 3months?	☐☐ times
AC. 17	If yes, how long did it take until RSF people were there to fix?	☐☐ days
AC. 18	Did they manage to f ix the problem?	☐ 1. Yes ☐ 2. No. What happened? ---
AC.19	How often do you receive visits from RSF staff per month?	☐☐ times
AC.20	Are these visits only for collection or also for fixing?	☐ 1. Yes, only for collection ☐ 2. No, also for fixing, how many in the last three months? ☐ times
AC.21	Did you miss any payments in the last three month?	☐ 1. Yes, why? --- ☐ 2. No

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Multi-tier Framework Questionnaire: Bangladesh

AC.22	What is your level of satisfaction of the system? (1 being very low; 6 being very high)	1 2 3 4 5 6 ☐ ☐ ☐ ☐ ☐ ☐
AC.23	What is your level of satisfaction of the service? (1 being very low; 6 being very high)	1 2 3 4 5 6 ☐ ☐ ☐ ☐ ☐ ☐
AC.24	Is there anything you would like to change in the current payment model?	☐ 1. Yes, what? -- ☐ 2. No
AC.25	Is there anything you would like to change in the current service model?	☐ 1. Yes, what? -- ☐ 2. No
AC.26	When was the system installed?	d d m m y y ☐☐☐☐☐☐

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Multi-tier Framework Questionnaire: Bangladesh

MODULE D: PRODUCTIVE USE OF ENERGY

NOTE: Please select members of household who replies YES to question 0.9

Only business owners and self-employed/freelancers working within the targeted area will be considered.

D.01	D.02	D.03	D.04	D.05	D.06	D.07
CODE	Who in the household manages a business or an enterprise? LIST UP TO 2 FROM HOUSEHOLD ROSTER (roster HH code 0.2)	What is the nature of the business activity that you own? 1. FARMER (SPECIFY CROPS) 2. LIVESTOCK/POULTRY 3. FISHERY 4. TRANSPORT/DRIVER 5. CONSTRUCTION 6. HOUSE REPAIR /CARPENTRY 7. MECHANIC 8. DOMESTIC HELP/ MAID 9. TAILORING/SEWING 10. POTTERY 11. BLACKSMITH 12. TRADE/ RETAIL SHOP (SPECIFY) 13. PHYSICIAN/ HEALER 14. HAIRDRESSER/BARBER 15. OTHERS/ SPECIFY	Where do you operate this [ENTERPRISE]? READ RESPONSES 1. HOME (INSIDE RESIDENCE) 2. HOME (OUTSIDE RESIDENCE) 3. INDUSTRIAL SITE 4. TRADITIONAL MARKET PLACE 5. COMMERCIAL AREA SHOP 6. ROADSIDE 7. OTHER FIXED PLACE 8. MOBILE	Do you run this business alone or you have partners? READ RESPONSES 1. ALONE/ no partner 2. ONE PARTNER –shared profit 3. TWO PARTNERS- shared profits 4. OTHER (SPECIFY)	On average, how long is your working day?	How many employees do you have?
1						
2						
3						
4						
5						

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Multi-tier Framework Questionnaire: Bangladesh

		Lighting*	ICT & Entertainment*	Motive power*	Cooling	Product heating*	Water heating*
Relevance	8. Please indicate which of the following application you **consider strictly necessary** to enable you to undertake your productive activity?	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No
Relevance	9. Would the lack of this application significantly make your business suffer in one of the following aspects:	1. Productivity 2. Sales 3. Costs 4. Quality	1. Productivity 2. Sales 3. Costs 4. Quality	1. Productivity 2. Sales 3. Costs 4. Quality	1. Productivity 2. Sales 3. Costs 4. Quality	1. Productivity 2. Sales 3. Costs 4. Quality	1. Productivity 2. Sales 3. Costs 4. Quality
Applications	10. Please indicate if you **regularly use** each of the following applications in your productive activity?[3]	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No
Applications	10a. For those you do use regularly, at what time do you use them most?	10am-2pm ☐	2pm-6pm ☐	6pm10pm ☐	10pm-2am ☐	2am-6am ☐	6am-10am ☐
Applications	11. If you indicated an application that you consider strictly necessary for your productive activity but which you do not use regularly, (7 is Yes and to 9 is No), please indicate **which is the most important reason why you do not use the application**. (Select from Code A)						
Energy Source	12. What is the **primary energy source** being used for this application? (Select from code B)						
Energy Source	13. If non-BLEN[4] fuel: Is your primary equipment of fuel combustion (e.g. stove) for this application?	1. Self-made 2. Manufactured	1. Self-made 2. Manufactured	1. Self-made 2. Manufactured	1. Self-made 2. Manufactured	1. Self-made 2. Manufactured	1. Self-made 2. Manufactured
Energy Source	14. IF non-BLEN fuel: Do you use a smoke extraction device? (e.g. chimney, hood)	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No
Seasonality	15. In the last 3 months, does the availability of your primary source of electricity vary across seasons?	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No
Seasonality	16. If yes, which is the most difficult season for electricity supply in your household? Please respond to all the next questions considering the worst season of the year	I. Monsoon II. Non-Monsoon					
Capacity	**Report the capacity of the system in WATT : read the value from the name plate of the electricity supply equipment. If not available read question 16.**	______ W or ______ Wh	______ W or ______ Wh	______ W or ______ Wh	______ W or ______ Wh	______ W or ______ Wh	______ W or ______ Wh
Capacity — **Electricity**	17. What is the capacity (in watts or watt hours[5]) of your primary source of electricity for this application?	______ W or ______ Wh	______ W or ______ Wh	______ W or ______ Wh	______ W or ______ Wh	______ W or ______ Wh	______ W or ______ Wh
Capacity — **Electricity**	18. Which of the following electrical appliances (see Code D) do you run with the primary energy source?						
Capacity — **Electricity or RM&T or A&H**	19. Does the capacity of the primary energy source cover your needs for this application?	1. Totally[6] 2. Largely[7] 3. Partially[8] 4. No or little[9]	1. Totally 2. Largely 3. Partially 4. No or little	1. Totally 2. Largely 3. Partially 4. No or little	1. Totally 2. Largely 3. Partially 4. No or little	1. Totally 2. Largely 3. Partially 4. No or little	1. Totally 2. Largely 3. Partially 4. No or little

[3] If answer is NO only ask question 8 and then the questionnaire is over for this application.
[4] Non-BLEN refers to kerosene, biomass, biofuels, diesel, gasoline and other petroleum products (BLEN stands for Biogas, LPG, Electricity and Natural Gas)
[5] For grid, mini-grid and fuel-based electricity generators (fossil fuel, biofuels, biogas), capacity is measured in watts. For all other off-grid systems, capacity is measured in watt hours.
[6] Totally means 100% of the needs are covered
[7] Largely means between 75% and 100% of the needs are covered
[8] Partially means between 25% and 75% of the needs are covered

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Multi-tier Framework Questionnaire: Bangladesh

Duration/ Availability	Electricity or RM&T or A&H	20. [During the worst season/in the last 3 months] , out t of the average number of hours you are working each day, how many hours is the primary energy source available for running the following application (should you decide to use it)?	☐☐ [hours]	☐☐ [hours]	☐☐ [hours]	☐☐ [hours]	☐☐ [hours]	☐☐ [hours]
	Fuel	21. [During the worst season/in the last 3 months] What percentage of you needs are you able to cover with the average quantity of fuel available for running the following application? To be rephrased?	1. <25% 2. 25%-50% 3. 50%-75% 4. 75%-100% 5. 100%+[10]	1. <25% 2. 25%-50% 3. 50%-75% 4. 75%-100% 5. 100%+	1. <25% 2. 25%-50% 3. 50%-75% 4. 75%-100% 5. 100%+	1. <25% 2. 25%-50% 3. 50%-75% 4. 75%-100% 5. 100%+	1. <25% 2. 25%-50% 3. 50%-75% 4. 75%-100% 5. 100%+	1. <25% 2. 25%-50% 3. 50%-75% 4. 75%-100% 5. 100%+
		22. [During the worst season/in the last 3 months] On average, how many times do you face unpredictable interruptions of your primary source of electricity per week? (Add a definition of interruption)	☐☐ *interruptions*	☐☐ *interruptions*	☐☐ *interruptions*	☐☐ *interruptions*	☐☐ *interruptions*	☐☐ *interruptions*
		23. [During the worst season/in the last 3 months] On average, how long is **each** unpredictable interruption of your primary source of electricity?	☐☐ [hours] ☐☐ [minutes]	☐☐ [hours] ☐☐ [minutes]	☐☐ [hours] ☐☐ [minutes]	☐☐ [hours] ☐☐ [minutes]	☐☐ [hours] ☐☐ [minutes]	☐☐ [hours] ☐☐ [minutes]
		24. How do unscheduled interruptions to energy access for this application impact your business operations[11]?	1. A little or not 2. Moderately 3. Severely	1. A little or not 2. Moderately 3. Severely	1. A little or not 2. Moderately 3. Severely	1. A little or not 2. Moderately 3. Severely	1. A little or not 2. Moderately 3. Severely	1. A little or not 2. Moderately 3. Severely
Quality	Electricity	25. [During the worst season/in the last 3 months] have you experienced situations in which appliances cannot be used or may get damaged because of low voltage or voltage fluctuations from the primary source?	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No
	Fuel	26. [During the worst season/in the last 3 months] did you face problems of adulteration or fluctuating calorific value of the fuel resulting in poor combustion[12] or slower RPM? Simplify language	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No
	RME or A&H	27. [During the worst season/in the last 3 months] did you face problems of low or fluctuating RPM (e.g. due to variable wind speed or water flow) or speed? Simplify language	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No
	RTE	28. [During the worst season/in the last 3 months] did you face problems of low or fluctuating heat or temperature? **In each attribute? Needs explanation**	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No
		29. How does inadequate quality of energy supply impact your business operations or to what extent has it damaged any equipment for each of the applications you use[13]?	1. A little or not 2. Moderately 3. Severely	1. A little or not 2. Moderately 3. Severely	1. A little or not 2. Moderately 3. Severely	1. A little or not 2. Moderately 3. Severely	1. A little or not 2. Moderately 3. Severely	1. A little or not 2. Moderately 3. Severely

[9] No or little means that less than 25% of the needs are covered
[10] 100% of the needs are covered and there are no constraints in extending operating hours
[11] The definition of the impact level (little or not; moderately; severely) is left to the respondent's perception within the context of his/her business and experience.
[12] Poor combustion may be the result of wet biomass, or adulterated fuel, resulting in weak flame, excessive black smoke, etc.
[13] The definition of the impact level (little or not; moderately; severely) is left to the respondent's perception within the context of his/her business and experience.

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Multi-tier Framework Questionnaire: Bangladesh

Health and Safety		30. [During the worst season/in the last 3 months] has your primary energy source for this application caused any health issue (i.e. Electrocution; smoke/fumes; Burns; Fire; Injuries etc.	1. Yes 2. No→**D.32**	1. Yes 2. No→**D.32**	1. Yes 2. No→**D.32**	1. Yes 2. No→**D.32**	1. Yes 2. No→**D.32**	1. Yes 2. No→**D.32**
		31. IF YES, what level of damage has caused?	1. Severe damage[14] 2. Moderate damage[15] 3. No or little damage	1. Severe damage 2. Moderate damage 3. No or little damage	1. Severe damage 2. Moderate damage 3. No or little damage	1. Severe damage 2. Moderate damage 3. No or little damage	1. Severe damage 2. Moderate damage 3. No or little damage	1. Severe damage 2. Moderate damage 3. No or little damage
		32. Does your primary energy source for this application likely to cause any health issue (i.e. Electrocution; smoke/fumes; Burns; Fire; Injuries etc.	1. Yes 2. No→**D.34**	1. Yes 2. No→**D.34**	1. Yes 2. No→**D.34**	1. Yes 2. No→**D.34**	1. Yes 2. No→**D.34**	1. Yes 2. No→**D.34**
		33. IF YES, what level of damage is likely to cause?	1. Severe damage[16] 2. Moderate damage[17] 3. No or little damage	1. Severe damage 2. Moderate damage 3. No or little damage	1. Severe damage 2. Moderate damage 3. No or little damage	1. Severe damage 2. Moderate damage 3. No or little damage	1. Severe damage 2. Moderate damage 3. No or little damage	1. Severe damage 2. Moderate damage 3. No or little damage
Legality	**Electricity**	34. Who do you pay for your primary electricity supply? (Select from code C)						
		35. Does your household have a meter for the primary source of electricity?	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No
Affordability	**Electricity**	a. **If metered connection** (grid or mini-grid): [During the worst season/in the last 3 months] what is the price per kWh that you pay? b. [This price excludes any fixed fees, connection fees, etc.]	______ Tk.					
		c. **If flat rate[18]** (grid, mini-grid or solar stand-alone system): [During the worst season/in the last 3months] what is the monthly flat rate that you pay in the last 3 months?	______ Tk.					
		d. **If rechargeable battery[19]**: [During the worst season/in the last 3 months] how much does it cost to recharge one of your batteries each time?	______ Tk.					
		e. **If fuel based generator[20]**: [During the worst season/in the last 3 months] what is the average price per litre or kg or m^3 that you pay for fuel to power your generator in the last 3 months?	______ Tk.					

[14] Severe damage means death or permanent limb/organ failure or incapacity for > 1 week.
[15] Moderate damage means damage (short of death, permanent limb/organ failure or incapacity for > 1 week) which requires medical treatment or time off work or is likely to cause a reduction in lifespan.
[16] Severe damage means death or permanent limb/organ failure or incapacity for > 1 week.
[17] Moderate damage means damage (short of death, permanent limb/organ failure or incapacity for > 1 week) which requires medical treatment or time off work or is likely to cause a reduction in lifespan.
[18] To obtain the price per kWh, the flat rate will be divided by the capacity (information obtained through question 11 or estimated based on information gathered from the mini-grid operator).
[19] To obtain the price per kWh, recharging cost will be divided by the capacity of a rechargeable battery (information obtained through question 11 or estimated).
[20] To obtain the price per kWh, the price per litre is multiplied by the number of liters needed by kWh (e.g. for diesel it is estimated at 3 litres/kWh).

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Multi-tier Framework Questionnaire: Bangladesh

	Fuel[21]	f. [During the worst season/in the last 3 months] What is the average price per litre or kg or m^3 that you pay for fuel to power your equipment?	______ Tk.					
	RM&TE or A&H	g. [During the worst season/in the last 3 months] How much do you spend on **average per month** for running the following application? h. [The price excludes capital and maintenance costs]	______ Tk.					
	36. [During the worst season/in the last 3 months], how many hours in a week on average do you spend on collecting, producing, purchasing your primary energy source for the following applications?		☐☐ [hours] ☐☐ [minutes]	☐☐ [hours] ☐☐ [minutes]	☐☐ [hours] ☐☐ [minutes]	☐☐ [hours] ☐☐ [minutes]	☐☐ [hours] ☐☐ [minutes]	☐☐ [hours] ☐☐ [minutes]
	37. [During the worst season/in the last 3 months]How many hours in a week on average do you (or any of the members of your productive activity) spend on maintaining (cleaning, oiling, repairing) the primary energy source used for the following application?		☐☐ [hours] ☐☐ [minutes]	☐☐ [hours] ☐☐ [minutes]	☐☐ [hours] ☐☐ [minutes]	☐☐ [hours] ☐☐ [minutes]	☐☐ [hours] ☐☐ [minutes]	☐☐ [hours] ☐☐ [minutes]
	38. [During the worst season/in the last 3 months]Does spending the time above (question 32 and 33) subtract relevant time to your productive activity and reduce business productivity?		1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No	1. Yes 2. No
	39. Which alternative energy sources that could significantly reduce the time and/or effort involved? (Select from Code B)							

* Application definitions:

1) Lighting: Use of energy to light working spaces to enable workers to undertake tasks, and for the comfort of customers (particularly in retail and hospitality).
Examples: task lighting, general lighting, security lighting

2) ICT: Use of energy for computing, electronics and other communication and audio-visual purposes
Examples: computing, communications (including phone charging), photography, photocopying, printing and media (radio/TV/sound systems)

3) Motive power: Mechanical uses of energy in which motion (either linear or rotational) is imparted to machinery
Examples: ploughing, harrowing, planting, irrigation, hoeing/weeding, harvesting, logging/felling, digging, lifting, grinding, milling, hulling, sawing, planning, drilling, turning, pumping, throwing (pots), sewing, cutting, spinning, weaving, air circulation, air conditioning, refrigeration, freezing, mechanical printing

4) Space heating: Use of energy to heat interior working spaces for the welfare and comfort of workers and customers
Examples: local space heating and central heating

5) Product heating: Uses of energy for heating as a direct part of the production process
Examples: cooking, baking, firing, drying, distilling, brewing, curing, smoking, forging, smelting, annealing, welding, soldering, ironing, incubating, pasteurizing, dissolving substances, sterilizing.

6) Water heating: Use of energy to heat water for hygienic and cleaning purposes[22]
Examples: heating, boiling, steam production (eg for wood bending), evaporation

[21] Each unit of fuel (litre, kg, m3) will be converted into the equivalent in kWh. The derived unit price per kWh equivalent will be then compared with the grid tariff. Affordability will not be assessed for fuels used for transport.

[22] Water heating as a means of achieving space heating is regarded as part of Space Heating

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Multi-tier Framework Questionnaire: Bangladesh

Code A (single answer)	Code B (single answer)		Code C (single answer)
I. Energy is not available in the area II. Energy in not affordable III. Appliance is not available IV. Appliance in not affordable V. Load shedding VI. Other (specify)	Electricity	I. IPS II. Solar lantern III. Solar stand-alone system IV. Rechargeable battery V. Electricity generator VI. Mini grid VII. National grid connection from [*name of utility*]	I. Local representative/official of the energy company II. Pre-paid meter card seller III. Community/village/municipality IV. Neighbour V. Land lord VI. Fuel purchase to power generator VII. PO VIII. None IX. Others (specify)
	Fuel	VIII. Direct use of biomass (fuel wood, charcoal,..) IX. Direct use of biofuels X. Direct use of biogas XI. Direct use of natural gas XII. Direct use of kerosene XIII. Direct use of LPG XIV. Direct use of diesel, gasoline, and other petroleum products (except kerosene & LPG)	
	RME	XV. Direct use of wind energy XVI. Direct use of water energy	
	RTE	XVII. Direct use of solar energy	
	A&H	XVIII. Animal power XIX. Human power	
		XX. No energy sources	

Code D (multiple answers)					
Lighting	**ICT**	**Motive power**	**Cooling**	**Product heating**	**Water heating**
a___# of fluorescent bulbs b___# of halogen (PAR) bulbs c___# of incandescent lamps d___# of LED bulbs e___# of LED streetlights f___# of sodium streetlights	___Camera charger ___Cell phone charger ___DVD player ___Fax machine ___Internet router ___Hand-held computing device ___Personal computer ___Photocopier ___Portable media player ___Printer (inkjet) ___Printer (laser) ___Projector ___Radio ___Recording device (industrial) ___Satellite decoder	___Belt sander ___Cold room ___Drill (electric hand drill) ___Drill machine <16mm ___Drill machine 16-40mm ___Drill machines 41-50mm ___Excavator <1,200 kg ___Excavator >1,200kg ___Grain mill (<13kg per hour) ___Grain mill (13-50kg per hour) ___Grain mill (51-250kg/hour) ___Grain mill (>250kg/hour) ___Hand plough/hoe ___Lathe (metal) ___Lathe (treadle) ___Lathe (wood) ___Milling machine 12-25mm	a___Air conditioner (central) b ___Air conditioner (industrial) ___Air conditioner (room) ___Fan (small table fan) ___Fan (standing fan or ceiling fan) ___Refrigerator/freezer (500 liters) -----Bought iceblocks	___Brewing kettle (2,000 liters) ___Brewing kettle (200 liters) ___Cooker, rice (domestic) ___Cooker, rice (commercial) ___Cooker (pressure cooker)) ___Cooker (commercial range cooker) ___Cooker (slow cooker, 3.5 liters) ___Distillation apparatus (1.5liter/hour) ___Distillation apparatus (5liter/hour) ___Electric burner (single) ___Electric burners (2) ___Electric burners (4) ___Fan for grain drying shed ___Forge (industrial)	___ Domestic electric shower ___Steam cleaner (3kg/hour at 4 bar) ___Steam generator (portable) (2kg/hour) ___Steam generator (23kg/hour) with 6000 cylinder ___Water heater (7-30liters)

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Multi-tier Framework Questionnaire: Bangladesh

	___Satellite dish ___Scanner ___Server (quad core) ___Server (system) ___Server room power distribution unit ___Television (black & white) ___Television (color) ___VHS ___Voice recorder	___Potter's wheel <25kg clay ___Potter's wheel 30-50kg clay ___Power loom ___Saw (chain) ___Saw (circular) ___Saw (rip saw) ___Sewing machine ___Spinning wheels/machines, looms ___Vacuum cleaner ___Washing machine (domestic) ___Water pump <3m^3/hour over <30m head ___Water pump 3-4m^3/hour over 30-70m head ___Water pump 5-80m^3/hour over 30-70m head		___Grain dryer >10Te/hour ___Grill ___Hair dryer ___Incubator (25-400 eggs) ___Iron (cloth iron) ___Kettle (domestic, 1,7 liters) ___Metal arc welding (500A) ___Microwave (commercial) ___Microwave (domestic) ___Oven (commercial) ___Oven (domestic) ___Pasteurizer (5,000 liters/hour) ___Pottery kiln 1,300^{o}C (>140 liters) ___Pottery kiln 1,300^{o}C (25-140 liters) ___Soldering iron ___Tea dryer ___Toaster ___Tobacco curing kiln fan ___Wood-drying kiln (46m^3)	

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Chapter 6

Swarm Electrification: Investigating a Paradigm Shift Through the Building of Microgrids Bottom-up

"Any intelligent fool can make things bigger, more complex, and more violent. It takes a touch of genius and a lot of courage to move in the opposite direction."

- E.F. Schumacher, 1973
2014

Chapter 1
Swarm Electrification: Investigating a Paradigm Shift Through the Building of Microgrids Bottom-up

Sebastian Groh, Daniel Philipp, Brian Edlefsen Lasch and Hannes Kirchhoff

Abstract The study investigates a bottom-up concept for microgrids. A financial analysis is performed through a business model approach to test for viability when replacing a researched energy expenditure baseline in Bangladesh. A case study of Bangladesh illustrates the potential for building on the existing infrastructure base of solar home systems. Opportunities are identified to improve access to reliable energy through a microgrid approach that aims at community-driven economic and infrastructure development. Network effects are generated through the inclusion of localized economies with strong producer-consumer linkages embedded within larger systems of trade and exchange. The analyzed approach involves the linkage of individual stand-alone energy systems to form a microgrid that can eventually interconnect with national or regional grids. The approach is linked to the concept of swarm intelligence, where each individual node brings independent input to create a conglomerate of value greater than the sum of its parts.

Keywords Energy access · Bottom-up · Microgrids · ICT · Bangladesh

Introduction

Across the developing world, considerable amounts of national incomes are invested in infrastructure development, such as the national electricity grid (Dobbs et al. 2013). Still they fail to cater to large shares of their (rural) populations, as 1.3 billion people lack access to basic electricity (IEA 2012). For an acceleration of economic and social development these challenges need to be addressed as they are inhibiting—or at least delaying—people's development paths (Groh 2014).

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Higher and more volatile resource costs and infrastructure resilience to climate change are yet to be adequately considered. It is against this framework that McKinsey's Global Institute has set out the trillion dollar question on infrastructure productivity (Dobbs et al. 2013). The study, however, is often centered on two key players of development: the government and the private sector. This approach fails to take into account "the crucial third agent, in whose name development is carried out: people organi[z]ed as communities and collectives, people seen not as 'beneficiaries' of the state or 'consumers' of private services but as drivers of their own destiny, empowered to self-provision basic needs and to govern from below" (Kothari and Shrivastava 2013). This research investigates a new conceptual approach on rural electrification where the infrastructure of a microgrid is built through the people's own resources from the bottom-up. Experience has shown that user-centered concepts can contribute to the pursuit of sustainable and effective energy access models (Tenenbaum et al. 2014). Grid-based solutions, on the other hand, can offer great potential to provide stable and sufficient electricity supply for productive uses, which play a key role in bolstering economic development (Kaygusuz 2011). Here, discussions usually follow a dichotomous character (Tenenbaum et al. 2014). There are either centralized (e.g. national grid extension) or decentralized solutions (e.g. stand-alone SHS or isolated microgrids). Hence, the economic calculus is based on the (non-) viability of grid extension, which is measured by the distance-based cost of extension. Remote villages with low load factor and demand need to be electrified with a "second class" solution through a decentralized approach (Mandelli and Mereu 2013). Further, discussions are often reduced to on-grid and off-grid population, leaving potential solutions for an estimated one billion people out of scope (AGECC 2010). This group has been referred to as the "temporarily on/off-grid sector" and is further targeted in the step-wise electrification approach presented here (Groh 2014, p. 85). Furthermore, a consensus has been formed on the imminent need of low carbon development scenarios for developing countries in order to prevent dangerous anthropogenic climate change but without undermining their development goals (Jakob et al. 2013). Nussbaumer et al. (2012), Sovacool (2012) and Pachauri (2011) give extensive overviews evaluating different approaches to measure energy poverty. Based on these articles, Groh (2014) discusses the financial implications of people living in remote areas for the case of Arequipa (Peru). A central result is that structural handicaps in the sense of deprivation of a certain level of energy service quality, physical and economic isolation from distribution systems and infrastructural poverty are key factors keeping people in their currently poor economic states. The authors assume that in certain scenarios a paradigm shift away from a top-down, centralized, and fossil-fuel based scheme will lead to better results in terms of economic and social impacts. Furthermore, the authors hypothesize that such a paradigm shift could improve existing decentralized methods for rural energy, including stand-alone one-off Solar Home Systems (SHS) and baseline energy fuels such as kerosene. This research seeks to test this hypothesis through the analysis of a newly developed sharing-based energy infrastructure approach, based on decentralized growth incentives and resource efficiency. The concept follows the principle of a bottom-up initiative in the sense that it is a decentralized track which is generally carried out through non-governmental entities such as cooperatives, community user groups, or private entrepreneurs. However, the concept further envisions a readiness toward the actors and infrastructure of the centralized track, being the utilities and the national electricity grid.

The objective of the study is therefore to investigate the feasibility of an approach where the people themselves start building upon their present resources in order to form a balancing network and prepare themselves for an eventual grid connection. The underlying research question raised here is to what extent a grid can be built bottom-up and in an economically sustainable way thereby meeting the challenges current trends in microgrids for rural electrification face. Based on previous research by Kampwirth (2009), Sarker et al. (2012) and Unger and Kazerani (2012) the authors elaborate on a bottom-up concept drawn from an approach that follows the basic principles of swarm intelligence in distributed information and communications technologies networks and test for its viability. In this scheme, each individual node brings independent input to create a conglomerate of value ostensibly greater than the sum of its parts. In the way that each node in a swarm intelligence network shares information with its neighbors to achieve a compounding network effect, individual stand-alone household energy systems could share electrical power—in that they are linked together to form a microgrid—to achieve a networked grid effect. Upon applying frameworks to evaluate the concept, a microgrid developed in this way appears to address myriad problems facing trends in rural electrification strategies that involve the dissemination of microgrids and/or individual household energy systems. This paper explores the trends and difficulties facing microgrid strategies for electrification, and then describes, analyzes and tests this bottom-up microgrid approach, which might be coined as "swarm electrification" for a developing country setting.

Objective and Methodology

The present paper builds on an extensive research on microgrid deployments around the globe based on literature review as well as wide-ranging field experience. Based on this approach, it identifies key challenges when it comes to the development, design and implementation of microgrids, which largely account for the lack of success of rural electrification microgrids to date from a range of literature sources including practitioner reports. The overarching objective of the study is to provide tools for alleviating rural and urban energy poverty at the grassroots level and to consequently support the process of reaching the Millennium Development Goals (MDGs) (Ki-moon 2011). To reach this goal, it analyses a model of a sharing-based energy infrastructure, coined as swarm electrification. The objectives are to:

1. analyze the status quo of microgrid deployment in developing countries;
2. develop and analyze the layout of an alternative model where key challenges are addressed;
3. evaluate the designed system based on the factors identified in 1.

The swarm model is discussed in detail in terms of technological design and service delivery scheme through design thinking methodologies, and then tested for financial viability, and finally further analysis necessary for a proof of concept are suggested. The study relies on a diverse set of methods, including literature research, design thinking for model conceptualization and cost-benefit analysis. Baseline energy expenditures and business model characteristics for the case study are collected based on data set analysis, on-site field research and interviews of key stakeholder active in the Bangladeshi rural electrification market. A financial sensitivity analysis model is developed for the swarm concept and tested for viability in comparison with the collected data, including data for un-electrified baselines as well as status quo one-off electrification solutions. Financial viability analysis is carried out through a comparative cash flow analysis in different scenarios for the case of Bangladesh. Moreover, the net present value (NPV) method is applied where each cash flow (incoming and/outgoing) is discounted to its present value and summed up, as shown hereafter:

$$NPV(r,N) = \sum_{t=0}^{N} \frac{C_t}{(1+r)^t},$$

where
t is the time of the cash flow,
r is the discount rate, and
C is the cash flow.

In order to come up with an initial pricing model, the levelized cost of electricity (LCOE) is calculated based on the general formula given below:

$$LCOE = \frac{\sum_{t=0}^{n} \frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+r)^2}},$$

where
I_t is investment expenditure in the year t,
M_t is operation and maintenance expenditure in the year t,
F_t is fuel expenditure in the year t,
E_t is electricity expenditure in the year t,
r is the discount rate, and
n is the life of the system.

Literature Review

The UN General Assembly has declared the years 2014–2024 to be the "Decade of Sustainable Energy for All" (United Nations Foundation 2012), underlining the importance of supporting the roughly 1.3 billion people living without access to electricity. Groh (2014) introduces the concept of an energy poverty penalty arguing that poor energy services rooted in infrastructural handicaps inhibit or at the very least delay people's economic development. He states that "poor energy service quality can refer to insufficiencies, unreliability, dangers in usage, low durability, unfitness, lack of after-sales service and even non-affordability, in the sense of poor financial services" (Groh 2014, p. 83). As a consequence, better energy service quality could serve as an essential tool to fight the energy poverty penalty and ultimately help achieve the Millennium Development Goals (MDGs) (UNDP 2005). The "Energy for All Case" expects that only 30 % of rural areas can be electrified via connection to centralized grids, whereas 70 % of rural areas can be connected either with microgrids or with small stand-alone off-grid solutions (OECD/IEA 2011). Yadoo and Cruickshank (2012) estimate that about half of the 1.3 billion people living off-grid today could be best supplied with decentralized microgrids.

Marnay et al. (2011) note that in more innovative schemes where new sources are added to existing sources, integration of microgrids may be difficult from a centralized planner perspective, which is why the "thinking has moved to a structure wherein there are independent control nodes" (Marnay et al. 2011, p. 4). Although microgrids have been employed for village electrification already for over 30 years, there are only very few examples that can claim to be based on a long term viable model based on financial, managerial and technical criteria (Frearson and Tuckwell 2013). They describe the main barriers as securing a standardized and streamlined procurement system, establishment and governance processes, ready access to suitable finance, appropriate consumer consultation, hardware selection and integration, and developing effective operations and maintenance structures. The large initial capital investment and the related question of refinancing and ownership put a brake on many efforts to implement larger microgrids (Ulsrud et al. 2011). National utilities, that might have the capacity to maintain them, usually lack incentives to do so—being aware that it is often less profitable than the centralized grid considering the disproportionate amount of challenges of maintenance and operation (Goldemberg and Lucon 2010). As an alternative, community managed microgrids have emerged. Literature on these models remains scarce as it is considered a new field (Peterschmidt and Neumann 2013; Rolland and Glania 2011). Still, grey literature, in terms of project reports, indicates that these schemes often do not last very long and fail much earlier than expected. Often microgrids are designed with the goal of an equitable socio-economic development. As a by-product, there is evidence found for theft, non-payment and overuse leading to overall system failure. A paper on mini-grids in China states an overuse case with reduction of service provision from twelve to three hours per day (Shyu 2013).

These processes can be described as a form of the "tragedy of the commons" (Hardin 1968). In contrast, if the ownership is left to small and medium energy enterprises, a severe financing gap limits their capacity to scale to a degree required to run such a scheme (Kebir et al. 2013). Nonetheless, the International Energy Agency (IEA) argues that "smart grids could enable a transition from simple, one-off approaches to electrification (e.g. battery- or solar PV-based household electrification) to community grids that can then connect to national and regional grids" (IEA 2011). However, it must be ensured that the technologies allow for just grids, promoting equality and enable access even to low income households (Welsch et al. 2013). Therefore, starting with a low entry requirement is crucial. Sarker et al. (2012) suggest a DC-based microgrid with distributed generation where Solar Home Systems (SHS) can become connected to the local grid. A first investigation of a concept that starts small and develops step by step has been undertaken by Unger and Kazerani (2012), who have advocated for organically grown microgrids that start with the purchase of small lamps and eventually lead to village cluster-sized grid topologies. This study builds up on the ideas of a sharing-based energy infrastructure and draws conclusions to develop it further, constructing a service model through a case specific analysis for Bangladesh and testing it for financial viability. Good infrastructure can be evaluated based on the four As ("4A") criteria: affordability, accessibility, acceptability and availability (Weijnen and Ten Heuvelhof 2014). The following observations, deducted from the analysis above as well as extensive field experience, represent significant challenges facing centralized planning of microgrids, which so far have not been adequately addressed in implementation models. The authors realize that a successful bottom-up microgrid solution based on distributed renewable energy sources will have to address these challenges in order to comply with the 4A framework:

- Demand tends to grow once electricity is available;
- Pace of growth is hard to determine;
- Oversized systems are not economically viable;
- Undersized systems might fail to adequately perform and therefore hinder social acceptance and economic development;
- Productive use is enhanced with larger electrical loads.

The next chapter aims to take these issues under consideration when discussing the swarm electrification concept based on a case study approach for Bangladesh.

Analyzing the Model: Case Study Bangladesh

According to the World Bank, 40 % of Bangladesh's population, representing 65 million people, has no access to the national grid (World Bank Indicators 2013). Direct Current (DC) Solar Home Systems (SHS), currently consisting of a 20–85 Wp solar panel, battery, and charge controller, have begun to successfully electrify Bangladeshi rural communities through the Infrastructure Development

Company Limited's (IDCOL) national SHS program (IDCOL 2013). Close to three million SHS are already installed through microcredit schemes implemented by Partner Organizations (POs), who are expanding their customer base at a rate of 45,000–70,000 systems per month, making Bangladesh the fastest growing SHS market in the world. However, many households with an SHS do not fully utilize the electricity stored in their battery, resulting in a full battery by midday, and thereby limiting the generation potential of their systems by up to 30 % (Kirchhoff 2014). At the same time, some households may require electricity beyond what their systems can supply, especially during the rainy season, while at the same time others cannot afford a complete SHS at all and remain trapped in energy poverty. Mondal and Klein (2011) further point to the limits of SHS in terms of its potential to directly affect an individual household's ability to improve its income generation. There is a need for more cost effective, reliable and flexible electricity supply. In rural areas of Bangladesh, settlements tend to consist of various clustered areas where households are built closely together in a dense pattern. Hence, it is common to see clusters of households and small businesses with SHS.

Applying the concept of swarm electrification and interlinking these clustered SHS to form a microgrid, end-users could act as "prosumers", forming the core nodes of the microgrid and allowing the end-users to both consume electricity from the microgrid as well as feed electricity into the microgrid. Such an approach enables synergies with network effects generated through the inclusion of localized economies with strong producer-consumer linkages, allowing for local trade. Unlike traditional microgrid approaches, it crucially aims to make the most of the existing infrastructure assets as suggested by Dobbs et al. (2013), which are herein referred to as previously underutilized or unrecognized resources. In this way, participatory inclusion of community members based on existing equipment assets would build upon existing social acceptance of the technology and business models. In addition, up front capital costs associated with green-field microgrid development are heavily reduced. From a technical point-of-view, utilizing systems that are already sized for a particular household would allow nodes of the system to share power and thereby balance out seasonal mismatches. The batteries in the example of Bangladesh are already typically sized with three days of autonomy to bridge cloudy days. This capacity is not required during the non-rainy season and remains under-utilized in the status quo. In the given context, the swarm electrification approach could also be used to interlink multiple households with SHS to households without SHS. By forming a village-scale microgrid through the network connection of electricity-sharing homes, end-users could make use of their differentiated energy generation capacities and consumption patterns to allow for a more efficient and consistent source of energy supply for end-user households compared with the solely stand-alone systems.

Crucially, such a scheme would allow for a microgrid business model in which end-users have the ability to be remunerated for energy that is produced by their system and consumed by other end-users in the microgrid. In the following example, communications and payment management between households is administered by a smart charge controller, referred to as a swarm controller, which meters energy in- and outflows on a real-time display, serves as a data logger, and allows the end-user a basic modicum of control to toggle their system between island mode and microgrid-connected mode.

Regarding the service delivery model, depicted in figure below 1, the concept builds further on existing resources. The great success of the mobile phone industry has brought about an extensive network of local operators for topping–up mobile phones even in remote areas (Nique and Smertnik 2014). Energy delivery mechanisms and innovations have already made successful use of this proven model, by allowing users to top-up their electricity consumption allowance through equipment algorithm keys purchased at mobile phone retail points (Nique and Smertnik 2014). The success of this approach is therefore incorporated into the swarm grid example, allowing users to top-up their electricity consumption allowance by purchasing a numerical code and entering the number into their swarm controller at home. On-site sales, promotion, and after-sales technical services can be performed through identified *local champions* referred to as swarm area managers (SAMs). The SAMs are small local entrepreneurs who have access to a distribution chain and can become a primary provider of electricity for several households (e.g. shop-owners on the central market). They receive a microcredit in order to be able to build up a stock, receive a quota per unit sold and a percentage of the trade volume when handing out the scratch cards to the users to top-up their electricity balance. This implies that only the consumption of electricity is ‘taxed’ whereas the generation which is consumed directly or fed into the microgrid, is tax free. As the SAMs’ revenue is highly based on the network effects, there is an intrinsic incentive for the SAMs to service the evolving grid and generate more sales. The SAMs can visualize, manage, and analyze this data through a back-end software solution provided to them (Fig. 1.1).

In order to allow for a real income generation source, which is crucial to address productive use aspects of successful microgrid designs, end-users should also be able to cash out positive electricity balances that their systems have fed into the grid. At any point of the month, when they need more electricity, they can go to the local SAM and top-up or, in the reverse case of consistent net production, cash out. The latter element expands the pay-as-you-go (PAYG) model (Bladin 2007) by a cash-in-as-you-go (CAYG) element. This ability to cash out also provides direct incentives for efficient electricity use, as their balance on their meter increases as their consumption decreases, once they start feeding into the grid more from their own SHS. In the theoretical application of the swarm model, data loggers built into the swarm controllers will allow for close monitoring of supply and demand within the swarm grid. Depending on supply or demand surplus, additional households without generation capacity can be connected to the grid, or additional generation capacity can be installed by incentivizing entrepreneurial households to buy bigger panels, given that the ability to sell surplus electricity can be considered likely based on past consumption patterns and prices. Service supply areas need to be defined in order to avoid conflict between different SAMs.

Research shows that further implications for the people are the possibility of a more flexible usage of their electricity both in terms of amount of energy in

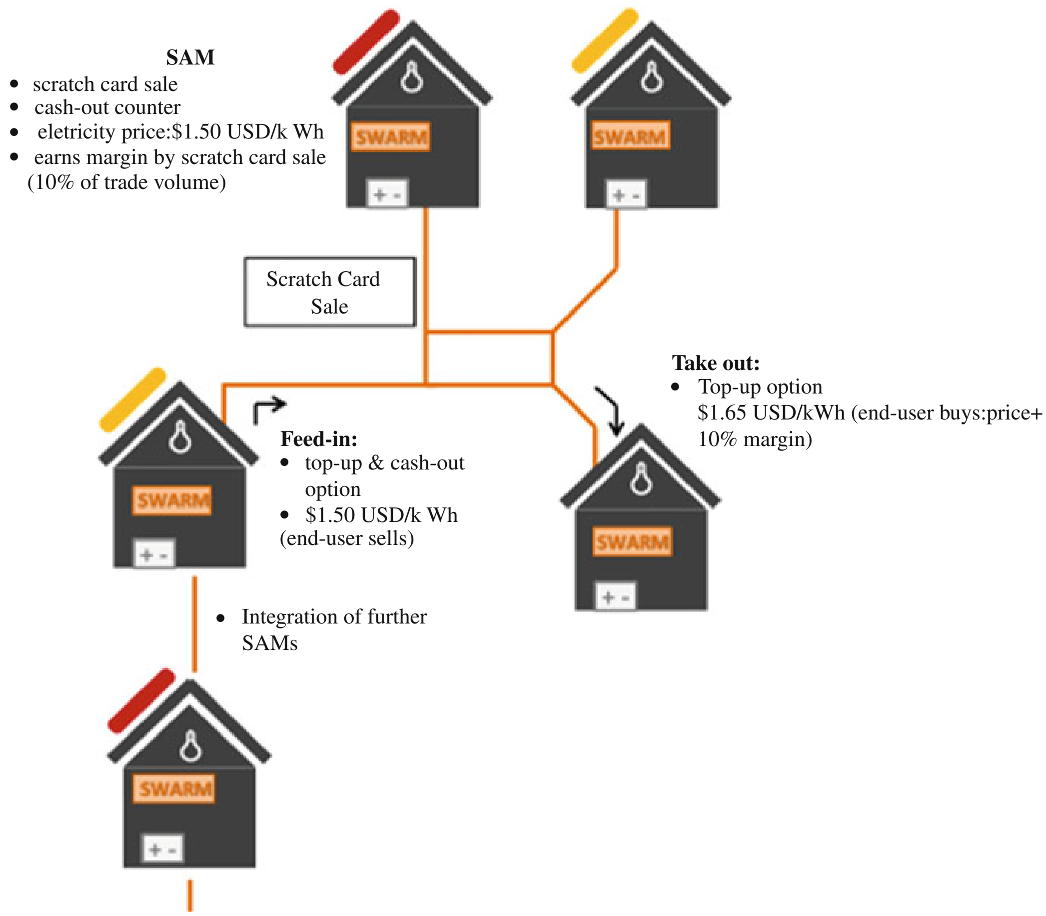

Fig. 1.1 Service delivery model through SAM scheme

Watt-hours (Wh) as well as in terms of time of usage, in addition to a likely improvement in battery state-of-health and prolonging of battery lifecycle based on fewer deep discharge incidents (Kirchhoff 2014). This style of rooftop decentralized generation further implies no centralized solar panel installations occupying large areas of useful land (as commonly seen in top-down microgrid designs), which is a major issue in such a densely populated country (Khan 2012).

The approach represents a democratization of electricity generation provided that the pricing scheme per unit of electricity is designed in a pro-poor approach. In Fig. 1.2, the step-wise approach of swarm electrification is shown. Step one shows individual households equipped with DC SHS as well as houses with neither solar nor grid electricity supply. Step 2 shows the interconnection of households with SHS, whereas in Step 3 the remaining houses are included in the growing DC microgrid. As a final step, the microgrid can be connected to a national or regional grid with minimal points of AC/DC conversion interfaces. With recent advances in smart grid technologies, such a bottom-up interconnected electrification approach becomes feasible (Unger and Kazerani 2012), however a financial and technical analysis must still be performed to fully understand the challenge and implications

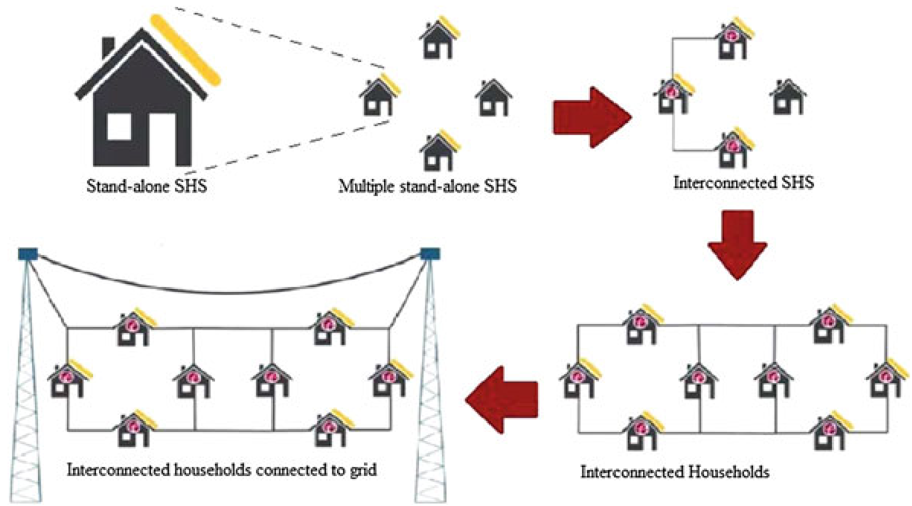

Fig. 1.2 Stepwise approach for swarm electrification. *Source* MicroEnergy International (2013)

of preparing a swarm microgrid for interconnection with a national grid distribution infrastructure.

The resulting network is a DC grid that can facilitate trade and increase usage flexibility and reliability beyond the status quo one-off systems. The trade of electricity allows SHS owners to generate additional income through the sale of excess electricity and consumption smoothing.

In a further investigation into commercial feasibility, current trading costs in the field have been used as baseline scenario. Key assumptions of the underlying models are summarized in Table 1.1 in the appendix. A SHS with a panel size of 50 Wp is modeled. The assumed photovoltaic system derate is set to 0.6.[1] In the presented simulation scenario the household is assumed to sell 29 % of its generated electricity, which is in line with Kirchhoff's previously calculated findings of approximately 30 % excess energy going unused given the limited storage capacity of the stand-alone system (Kirchhoff 2014). It does not, however, include any excess based on the rapidly growing application of more efficient DC-based appliances in the market.

Figures 1.3 and 1.4 show the viability of the approach in a simulation from an economic perspective. Figure 1.3 shows the time dimension measured in years on the y-axis whereas the x-axis indicates cumulative total electricity cost for the average off-grid household. The swarm concept requires an advanced charge controller to enable interconnection of SHS and sale and purchase of electricity between the systems. This scenario with such a controller is indicated with the name "Swarm Controller" in the figures. Assuming the electricity seller is purchasing a new SHS, three scenarios are compared: (1) the costs of continuing to meet electricity

[1] 40 % loss consisting of 20 % due to battery conversion losses, 13 % due to temperature and maximum power point mismatch, 5 % due to maintenance interruptions and 2 % due to cabling losses (Kirchhoff 2014).

requirements through kerosene and car battery, (2) purchasing a "Standard Controller" status quo SHS, and (3) purchasing an SHS with the "Swarm Controller".

Extensive field data[2] is used to estimate the green line indicating annual cost for kerosene and car batteries. The blue line represents the cost based on the SHS sales statistics of the past years. It is worth pointing to the fact that the current SHS microcredit scheme under which more than three million systems were sold does not compete with the present cost of kerosene and car batteries throughout the credit period of 36 months, but rather first breaks even only in year four (c.f. Fig. 1.3).

The red line dotted with squares in Fig. 1.3 indicates the electricity cost for a prosumer with a swarm controller over a lifetime of 10 years, where 30 % of the generated electricity of the 50 Wp SHS is traded/fed-into the microgrid. The green baseline is based on present expenditure for people relying on kerosene and car batteries whereas the blue baseline represents the monthly expenditure under the current microcredit scheme for SHS. The red line mimics the blue status quo SHS path despite its higher initial investment and outperforms the comparative scenarios after the credit has been paid off. Refer to Tables 1.1 and 1.2 in the appendix for details on cost and system sizing used for the simulation. Other advantages such as better system performance due to better battery recharging cycles, more flexible usage of electricity, better system integration and opportunities for increased income generation through acquisition of bigger panel sizes are not taken into consideration. On the other hand, it is assumed that all excess electricity generation can be and is sold within the microgrid. Figure 1.4 takes the perspective of a net consumer (without generation capacity), who pays for electricity consumed from the swarm microgrid.

The calculated NPVs indicate that additional electrification effort can be realized, especially for households who could not afford a full system before. By sharing the power generated from one household located at a particularly sun-exposed location, households that are located in a disadvantaged position for a solar-based system (e.g. in a shaded area) could also gain access to the microgrid electrification.

In that case these people can buy electricity at a lower cost compared to the business-as-usual case (represented by the blue line in Fig. 1.3) while renting a swarm controller and smaller-sized battery through a leasing scheme (represented by the red line). The latter case is designed to bring down monthly cost and initial down payment further down based on a linear depreciation assumption with ten years of expected system lifetime considering depreciation, deterioration and random failures, including a full replacement of the battery after five years. It is further worth noting in the comparison of Tables 1.1 and 1.2 in the appendix that the calculated NPV for a pure consumer (assumed to be a low-income household that could not afford an SHS) is considerably higher compared to a prosumer (slightly more than twice), given that the pure consumer experiences an assumed much stronger prevailing energy poverty penalty over a 10 year timeframe.

[2] Underlying data from Rural Electrification and Renewable Energy Development (RERED) II Project Report from the World Bank 2012.

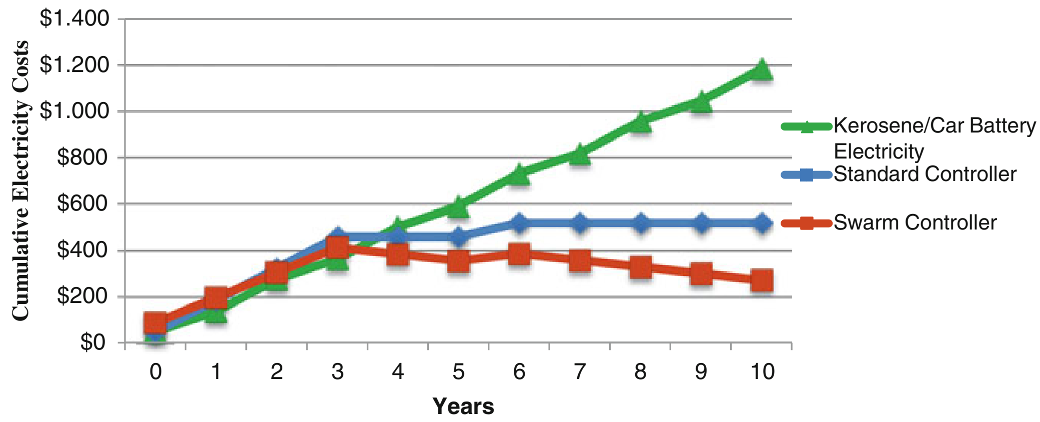

Fig. 1.3 Cost of electricity for an "equipped" electricity prosumer in a swarm scheme (*red line with squares*) versus baseline

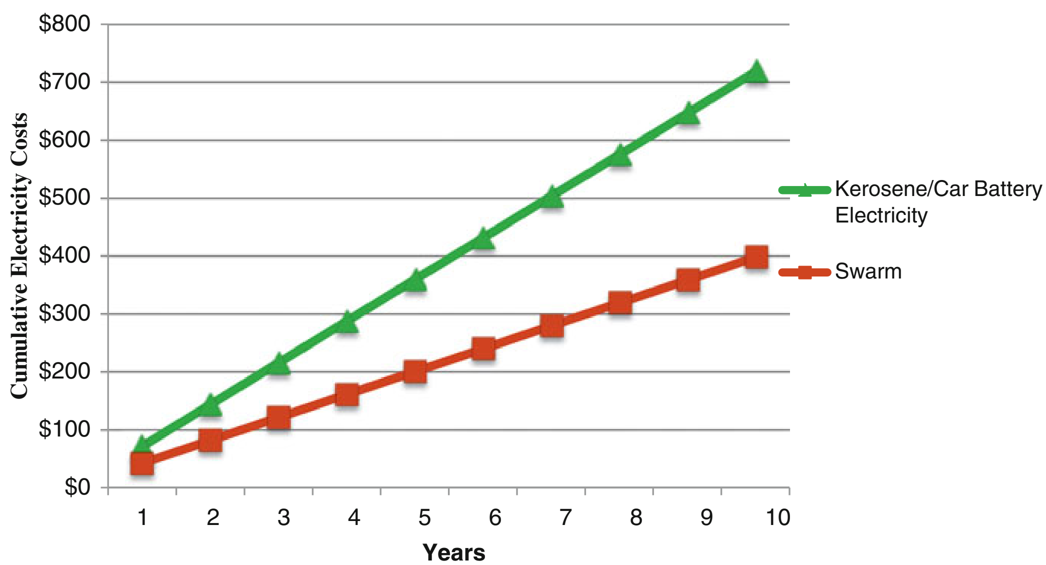

Fig. 1.4 Cost of electricity of an "un-equipped" electricity consumer in a swarm scheme versus baseline

A discount rate of 9 % is assumed, which is reasonable given an inflation rate of 7 and a 2 % risk premium (BBS 2014). Applying the 4A criteria to the concept, observations can be made. The scheme:

1. provides possibilities for flexible provision of electricity based on a mobile retail network already deeply rooted in the rural areas (accessibility),
2. results in favorable economics based on baseline data under a microcredit/-leasing scheme (affordability),
3. builds on network effects and existing resources and increases access to daily and seasonal energy through a balancing network (availability), and

4. utilizes a familiar technology and delivery model that builds on existing social acceptance (acceptability).

The concept allows the user a modicum of control to decide when they are operating in grid-connected mode or island mode, and avoids interpersonal conflicts and cash exchange through a system of digital credits and debits managed by the network of swarm controllers and with payments handled only by neutral mobile phone retail points.

Where the model potentially falls short is in direct comparison with microgrids is the ability to power large loads. Microgrids are designed from the start for increased power use beyond SHS (not just increased energy over time but larger instantaneous power draw for larger appliances). The swarm model might remain dependent on the existing SHS cabling and voltage levels, thereby retaining the instantaneous power draw limits of the SHS even if the overall energy availability and system performance increases. With regard to battery health, while Kirchhoff (2014) has shown that proper State-of-Health and State-of-Charge management are possible for the prosumers in such a scheme, it is not clear that this will be the case for the smaller batteries installed for pure consumers of the microgrid energy. The present simulation price at USD 1.50 per kWh (without any subsidies) is calculated based on the LCOE method considering that there are no running fuel cost, an initial investment based on current numbers in the Bangladeshi SHS program with the additional cost of the swarm controller and battery replacement after five years, 5 % of total investment (approx. USD 500) as yearly operation and maintenance cost,[3] electricity generation as shown in Table 1.1 in the appendix, the same discount rate as applied in the NPV calculations.

With regard to Operation and Maintenance (O&M), requirements largely synergize with the O&M requirements for status quo SHS (cleaning panels, refilling batteries with distilled water, replacing fuses), which are well-understood and regularly practiced by the target Bangladeshi communities. However, O&M of the grid infrastructure itself (running new cabling, preventing theft, repairing cabling, installing and checking safety devices, etc.) would need to be carefully considered for a sustainable business model, and could potentially also be conducted by the same POs instead of the SAM. It should be noted that a safe extra low voltage (SELV) can be chosen as the network voltage to mitigate the need for extensive safety training and equipment, as these voltages fall into the touch safe range. It is further important to note that the model is sensitive to changes in the electricity trading price per kWh, as well as the available and tradable amount of Wh (see Figs. 1.5, 1.6 and 1.7 in the appendix). The baseline scenario for the sensitivity analysis stands at a 50 Wp system, where 35 % of excess energy is generated[4] and

[3] Values based on ten year historical data of the Bangladeshi SHS program.

[4] This is higher than in the economic analysis in Fig. 1.3 (30 %), as well as that the purchaser consumes now 40 Wh (instead of 20 Wh per day). This is in line with a trend where excess energy will tend to increase due to appliances with higher efficiency built into existing systems as well as consumption will.

fully sold at a price of USD 1.50 per kWh for a system that is running for five years. The purchaser is assumed to buy 40Wh of electricity per day in order to cover her electricity needs. Figure 1.5 illustrates the trade-off between a very pro-poor approach with a trading price range of approx. USD 0.50 and USD 1.75 as the border conditions, displaying both prosumer and purchaser as well as the status-quo system owner. A price of USD 0.50 (considerably lower than the calculated LCOE of USD 1.45) puts the advantage on net consumers and people not able to afford a system of their own. A price of USD 1.75 sets the incentives completely on the net producer side to buy more generation capacity and sell off the excess while keeping purchaser still at par with the traditional monthly SHS system cost (note: consuming, however, only 40 Wh per day). Figure 1.6 shows that a SHS only needs to produce a little over 10 % of excess capacity in order to for this model to become feasible. Under the baseline of 35 % excess capacity, accordingly, at least 30 % of the excess needs to find a buyer in order to break-even.

If either supply or demand falls short, mitigation mechanisms exist through incentives for prosumers to become more of a producer when choosing panel size given the existence of a business opportunity. For the latter case, additional electrification of households too poor to afford a system can close the demand gap. The respective SAM might decide to utilize price differentiation that depends on factors such as distance from the nearest connecting household, the rate of power coming directly from the solar module or the battery, time of usage, or other variables. Further investigation is needed here.

Discussion and Conclusions

Despite the current trend toward traditional microgrids and one-off SHS solutions for rural electrification, the authors show that under presented conditions and assumptions the concept of swarm electrification may present a better fit to meet the combined goals of universal energy access for all and fostering rural economic development. The approach requires neither a large initial capital investment nor top-down system sizing. The key barriers addressed in section Literature Review appear to be adequately addressed in theory, as it builds on an existing and proven technology, end-user financing, delivery mechanisms and social acceptance trends, thereby meeting the criteria set out in the 4A evaluation scheme for good infrastructure (affordability, accessibility, acceptability, availability). Moreover, a tragedy of the commons problem is unlikely to occur in this case as the majority of individuals have their own system or supply, with the ability to choose to utilize their energy generation and storage equipment as income generating assets, monitored on an individual metering system without a centralized capped storage capacity, or to decide to run their system in an independent island mode.

The theoretical case study for Bangladesh indicates that the swarm concept is able to create win-win situations. Some simple cost-benefit calculations suggest that the process can be designed in a financially mutually beneficial way for end-users who are able to afford a complete SHS, as well as for end-users who are unable to afford a complete SHS and currently pay high prices for baseline energy sources such as kerosene and car batteries. Comparable calculations and simulations could be run for different settings on the one hand to test the degree of scalability and impact for the Bangladeshi off-grid sector but also for a feasibility assessment of potential replications in different country settings in terms of their existing resources and expenditure patterns, respectively. The financial model is based on network effects, and thus dependent on initial sales of swarm controllers gaining momentum, as well as being vulnerable to the potential occurrence of unexpected critical social acceptance issues. Furthermore, the concept requires a smart pricing mechanism in order to simultaneously incentivize consumers and producers as well as a local operator. The topic of potential solutions for ownership schemes of such a microgrid remains to be proven in real world implementation examples. From a technical perspective, solutions to enable increased power and thereby larger loads should be addressed if the infrastructure is limited by fixed SHS cabling and voltage levels. Safety and switching of DC distribution voltages need to be further investigated. An adequate agent-based control scheme, as outlined by Kirchhoff (2014), needs to be developed and field tested. These questions need further in-depth research. Although, the concept has a built-in opportunity for scalability, the issue of replication potential for other perhaps less densely populated countries remains to be seen.

The authors conclude that changing the mindset of prohibitive last mile cost (centralized perspective) to an end-user perspective and the peoples' own development capabilities may lead to increased success in rural electrification and pro-poor economic development schemes. As such, a paradigm change from top-down planned centralized microgrids toward a bottom-up microgrid approach where the decision and managing power is up to the people and their existing resources themselves without creating a common pool resource could have a positive impact on the development of economically and technically viable localized electricity distribution infrastructures. In this scenario, people are no longer obliged to wait for a utility grid extension, but start building a local grid themselves, beginning with individual household-level systems afforded through inclusive end-user financing and delivery mechanisms. The authors expect that in the future, microgrids based on these concepts will play an important role for decentralized energy supply in order to foster rural development. A paradigm shift in both research and practice could break down the traditional dualistic conception of rural electrification, where utility grid extensions or one-off stand-alone energy systems are pitted in competition, and allow for a productive exploration of innovative bottom-up energy access models.

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Appendix

See Tables 1.1 and 1.2; Figs. 1.5, 1.6 and 1.7.

Table 1.1 Cost scheme "prosumer"

SHS owner	
System size (W)	50
PV system derate	0.60
Daily system PV generation (Wh/day)	135
System voltage (V)	12
Battery size (Ah)	80
Max. battery % depth of discharge	50 %
% of generated electricity sold	30 %
Average Wh available to sell (Wh/day)	40
Average Wh available to sell/month (Wh/month)	1200
Levelized cost of electricity (USD/kWh)	$1.5
Monthly revenue from electricity sales (USD/month)	$1.80
Existing charge controller cost (USD)	$0
Swarm controller cost (USD)	$40
System sharing wiring cost (USD/prosumer)	$3
Swarm controller simple payback (years)	2.59
NPV (USD)	**$98.62**

Table 1.2 Cost scheme "consumer"

Electricity purchaser	Credit	Leasing
Swarm controller	$40	
Battery (10 Ah)	$25	
System sharing wiring (USD/consumer)	$3	
Hardware cost (USD/month)	$1.93[a]	$1.75[b]
Levelized cost of electricity (USD/kWh)	$1.5	
Daily usage (Wh/day)	20	
Monthly cost of electricity used (USD/month)	$0.90	$0.90
Total cost (USD/month)	$2.78	$2.65
NPV (USD)	**$321.38**	

[a] Calculated based on a 12 % yearly service charge (flat)
[b] Based on 5-year lifetime with linear depreciation model

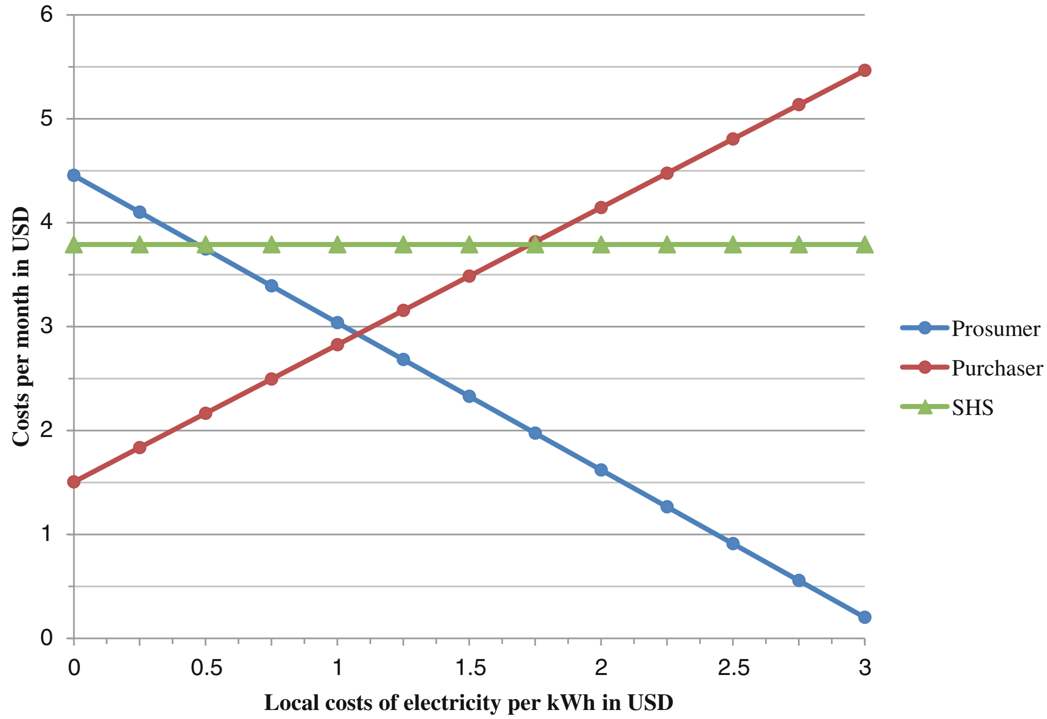

Fig. 1.5 Electricity trading price scenarios

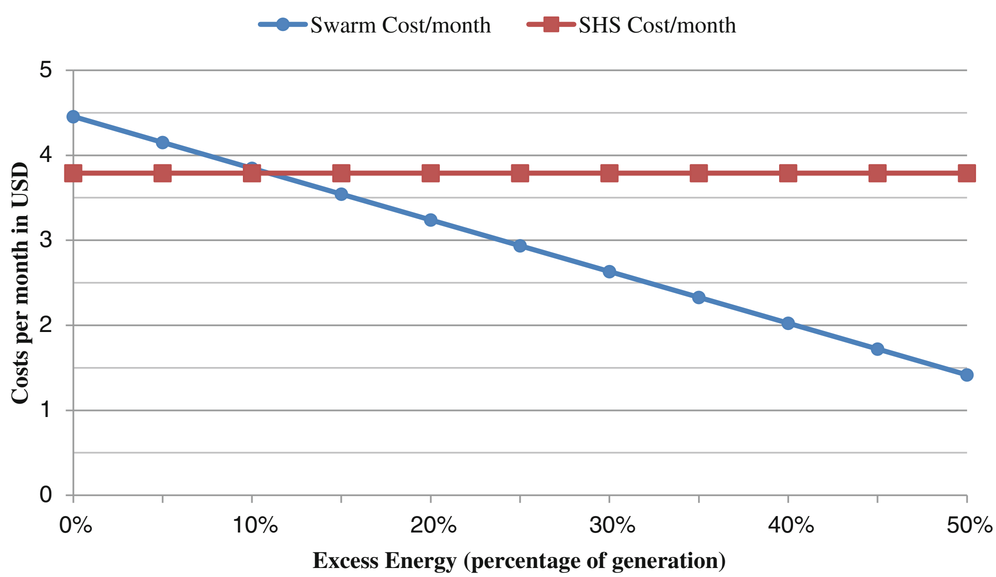

Fig. 1.6 Excess energy generation scenarios

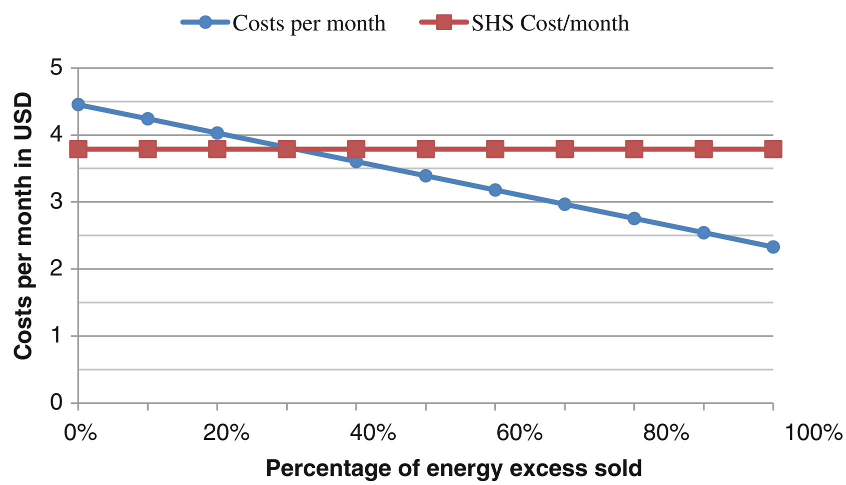

Fig. 1.7 Excess energy trading amount scenarios

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Chapter 7

Synthesis

"The test of our progress is not whether we add more to the abundance of those who have much; it is whether we provide enough for those who have too little."

- Franklin D. Roosevelt - Second Inaugural Address, 1937

Synthesis

The thesis stems from the hypothesis that many developing countries find themselves in a tight spot. On the one hand, there is enough reason to believe that an energy access problem stalls the development of its deprived citizens that in turn may trickle-up and hamper the country's overall development. On the other hand, the traditional approach of grid extension and intensification does not promise to solve the issue as often deemed economically unviable. As such, they are left off with an unclear picture of decentralized options that in the past repeatedly either failed to show any positive or were only of limited impact. The thesis therefore aims to shed some light on the measurement and design of interventions targeting energy poverty in a developing country context. The underlying corollary stems from the developed concept of an energy poverty penalty, analyzing energy service remoteness and a correlated energy poverty penalty. High capital expenditure (CAPEX) is found to prevent positive change. In specific cases, a phenomenon of redundant double infrastructures, which are often of competitive instead of complementary nature, exacerbate the issue, especially in the context of minigrids that frequently suffer from a special form of lock-in effects. Applying a multi-tier framework also shows the complexities involved when measuring energy access and evaluates different energy service interventions. Based on these findings, a novel design innovation, coined as swarm electrification, is derived as one possible way forward for rural electrification. These outcomes are based on the analyses in chapters 2 to 6 that looked at the role access to electricity plays in development processes in a sequential manner having used a set of different methodologies. They are summarized and discussed hereafter.

7.1 Energy service remoteness and the energy poverty penalty

Decentralized approaches are usually applied in areas we refer to as remote. Remoteness is here understood as acute energy isolation barriers, in terms of geographical distance, financial means and political power play preventing better access opportunities. Therefore, this first chapter gives impetus to the dissertation by looking at the following research question:

- *What is the relationship between energy poverty, remoteness and its implications for the people's development opportunities?*

Its underlying hypothesis is that an energy poverty penalty (EPP) is at play here, similar to the known concept of poverty traps. As such, energy poor people spend more money on energy in both relative and absolute terms as they pay a poverty premium. An empirical analysis of 342 households and micro-businesses in Arequipa (Peru) finds statistically signicant evidence for the existence of the EPP while controlling for income and infrastructural poverty/ structural handicaps. Mobile phone network coverage is used as proxy for remoteness criteria and to build data strata, thus facilitating model replication for different geographical areas and a systematic measurement of structural handicaps. It is further shown that it serves as a better proxy for remoteness than the mere measure of physical distance to the capital. The main implications are twofold: First, a deprivation of a certain level of energy service quality exacerbates the status of poverty and consequently delays or even impedes societal development opportunities. Second, a uni-directional (or at least bi-directional) causality running from energy service quality to economic development seems to be at play. Furthermore, observations are made that energy inclusion measures might "come at a cheap price" based on the strong HDI impact accompanied with small changes in energy consumption. Considering the decoupling effect observed in Peru based on its human and energy development index drift (for low levels), it is recommended that the focus on energy inclusion measures be intensified which − to follow the same logic − will eventually also lead to higher incomes in rural areas. In the first phase the lowest income segments should be targeted since analysis shows that the EPP is most prevalent there. As for the type of measures, it is recommended not to merely rely on subsidies on energy technologies, but investments into infrastructure facilitating the delivery of energy services. The recommendation is based on two results of this chapter. First , structural handicaps are among the key factors leading to the EPP and therefore need improvement efforts. Second, energy use is diverse, and so is the use of energy technologies. By investing into better delivery channels a multitude of technologies can be channeled toward the energy poor. Having said that, this type of support directly targets the group most affected by the EPP, instead of benefiting all through a product subsidy with less impact.

7.2 Minigrid system design: high CAPEX, redundancy and technological lock-ins

The thesis makes reference to microenergy systems (MES) as a set of potential technology approaches that bear the potential to approach an EPP. A MES is defined as a *"decentralized energy system based on small energy appliances, which provide households, public institutions, [and] small businesses with energy and enables energy demand to be met by locally-based sources"* [v.d. Straeten et al., 2014, pg. 139]. 70% of the rural off-grid population may gain access through MES, the majority, 65%, of these via minigrids and 35% via individual solar systems in their homes [IEA and WB, 2014]. The two chapters on minigrid system design pose the subsequent research questions:

- *What are critical design principles for minigrids that support all three SE4ALL goals in combination with a focus on productive use of the delivered energy?*
- *How can we contrast AC and DC microgrids in practice and theory based on their proficiency to deliver energy services?*

The first part hypothesizes an increasing transition of the Bangladeshi off-grid sector from solar home systems (SHS) to minigrids and shows how the SE4ALL goals can be translated into resource-efficient design principles by a) assuring reliable energy access, b) utilizing a high renewable energy fraction and c) incentivizing the use of energy efficient appliance technology. Emphasis is put on the electrification scope for productive uses through hybrid minigrids ranging from 100 to 250 kWp. The chapter is very rich in local data and information based on multiple demand assessments and actual design experience. Nonetheless, these types of minigrids have yet to prove both scale and commercial viability. A major drawback lies in its high CAPEX and an often underestimated OPEX.

The second part, in turn, focuses on a different technology design and sizing. It postulates that since distributed renewable energy generators as well as batteries deliver DC power and the majority of appliances being used in rural areas (can) run on DC, it follows that DC-based microgrids are a logical and efficient choice as a solution for electrification of remote areas. A comparative analysis is run based on the multi-tier approach to measuring energy access as well as a case study of a recent Bangladeshi DC-nanogrid of a few kWp is performed. Among the results are that current trends in the off-grid sector tend to favor DC microgrids that compare better in the comparative analysis conducted. Nevertheless, they remain low on up-take due to lock-in effects. These lock-in effects, however, do not occur based on prohibitive changing cost (greenfield energy access environment) but are due to a lack of confidence and knowledge transparency of the alternatives. Despite a long history as a potential MES, implementations of microgrids are still in its infancy. Given this prematurity, markets tend to stick with what is already familiar, including the configuration of AC utility grids originally promoted by Westinghouse. Therefore, researchers as well as practitioners are encouraged to step forward into this field and share latest research and implementation results of DC powered microgrids.

7.3 Measuring electricity access

Chapter 5, with the help of a set of 231 conducted questionnaires, applies a quantitative approach to assess the proficiency of energy interventions to provide electricity services in Bangladesh, as well as it digs deep into the metrics of the candidate multi-tier framework. The chapter follows the research questions hereafter:

- *To what extent does the candidate framework uphold its promise of measuring a continuum of improvement of the energy access status of a household based on the performance of its energy service supply?*

- *What are the missing links of Bangladesh's current energy interventions for reaching a higher tier assignment?*

Thus, it is the chapter's objective to provide feedback on the multi-tier framework's design, and suggest potential improvements, as well as to discuss its wider implications against the backdrop of current electricity access intervention programs in Bangladesh. Considering multiple attributes (dimensions) rather than a single binary indicator of access is a big positive step forward. Thus the multi-attribute framework is a definite improvement compared to previous measurement approaches. The study's results reveal a clear trade-off between capturing the multi-dimensionality of energy access and the simplicity of an easy to use global framework. Several attributes that determine the respective tier assignment need to be refined. Others, such as the capacity and affordability attribute require a careful re-design in order to reflect latest trends in appliance efficiency and payment methodologies (e.g. PAYG). Neither of the algorithms that connect the attributes with the tier assignment is ideal. In the given sample, access to the national grid does not necessarily imply a higher tier status than off-grid households receive. As the new framework allows for a reflection of country specific energy interventions, this paper for the first time evaluates the widely acclaimed solar home system program of Bangladesh. Currently, SHS are not reflected at all in (inter-) national statistics on energy access. According to the multi-tier framework, the sample households with SHS score at the tier 1 and at best at the tier 2 levels [1], depending on the application of the capacity attribute. Based on the latter criterion, eligible products under up-coming programs such as the IFC Lighting Bangladesh program do not even qualify for a tier 1 assignment. There is a clear need for action that address households at lower income levels, as present schemes

[1] Note: A last minute change in the definition of the capacity attribute of the multi-tier framework has been trying to fix this problem.

address largely higher income rural customers. The multiple matrices (supply, services, consumption) are found to be obsolete. Furthermore, it should be carefully noted that the tier assignments are highly sensitive to parameter changes, different algorithms, and data requirements. The performance evaluation of country specific energy interventions can therefore differ significantly, depending on the type of algorithm that is used. All algorithms for combining performance along individual attributes to assign a household to a particular overall tier are arbitrary (whether simple or any version of the complex) and inherently require some normative weighting of the individual attributes. This may lead to conflicts when it comes to building consensus for a universal measurement framework among the SE4ALL member countries. Once this is achieved, pro-poor policies that influence energy access by enabling households to achieve higher tier levels can be designed and implemented more effectively. In light of a likely inclusion of energy access in the upcoming SDGs, the chapter advocates for a fast review of the candidate framework and a quick adoption in the field through systematic integration in existing surveys or, what might be quicker and more prudent, to put it high on the agenda of the multilateral national offices of the SE4ALL member countries.

7.4 A novel approach to improving electricity access

The last chapter can be understood as an investigation of an innovative electricity access approach based on the analysis of the previous chapters on current technical, economic and social challenges encountered in literature and practice. It introduces the concept of swarm electrification that describes a process where each node in a swarm intelligence network shares information with its neighbors to achieve a compounding network effect; individual stand-alone household energy systems are linked together to form a microgrid, thereby achieving a networked grid effect based on the sharing of electrical power. The following question directs the research:

- *To what extent can a grid be built from the bottom-up in an economically sustainable way and to what extent such an approach can meet the challenges facing current trends in microgrids for rural electrification?*

The concept manages to sketch an energy development path where the technology enables a transition process based on existing resources. It shows how existing SHS in Bangladesh can get interconnected to form a dynamic grid from the bottom-up. Within this grid electricity can be traded enabling income generation opportunities and the provision of electricity to households that could not afford a SHS to date. Building on an existing and proven technology, end-user financing, delivery mechanisms and social acceptance trends, thereby meeting the criteria set out in a 4A evaluation scheme for good infrastructure (affordability, accessibility, acceptability, and availability) the approach requires neither a large initial capital investment nor top-down system sizing, both key barriers identified earlier in this thesis. Moreover, a tragedy of the commons problem is unlikely to occur in this case as the majority of individuals have their own system or supply, with the ability to choose to utilize their energy generation and storage equipment as income generating assets. These are monitored on an individual metering system without a centralized capped storage capacity, and they can decide to run their system in an independent island mode. Levelized cost of electricity and cost-benefit analysis dissect the approach under a Bangladeshi scenario. Although, the concept has a built-in opportunity for scalability, the issue of replication potential for other less densely populated countries remains to be seen. Further to this, drawback may occur once complexity increases when trying to gradually offer higher tier services. The chapter concludes that despite the current trend toward traditional microgrids and one-off SHS solutions for rural electrification, under presented conditions and assumptions the concept of swarm electrification may present a better fit to meet the proposed SDGs 7 (Ensure access to affordable, reliable, sustainable and modern energy for all) and 9 (Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation). A paradigm shift in both research and practice could break down the traditional dualistic conception of rural electrification, where utility grid extensions or one-off stand-alone energy systems are pitted in competition, and allow for a productive exploration of innovative bottom-up energy access models.

7.5 Discussion

7.5.1 Objective, overarching research questions and overall contribution to literature

It is the declared objective of the dissertation to study innovative approaches in facilitating access to electricity in the context of energy poverty. There were three overarching research questions rooted in the empirical challenges faced by the energy access sector set out at its beginning:

i *What is the relationship between energy poverty, different forms of remoteness and its implications for societal development opportunities?*

ii *How do we rate the proficiency to deliver energy service of different MES based on a multidimensional energy access framework?*

iii *To what extent can a smart energy intervention design overcome the challenges currently faced by minigrids designed for rural electrification?*

These questions rest upon the previously discussed individual research questions of each chapter which in turn each made a specific contribution to the literature on energy poverty and service innovation. That being said, there are three overarching contributions from the thesis as a whole to the literature on energy poverty:

i *The concept of an energy poverty penalty.*

ii *The explicit consideration and anticipation of the linkages between energy service provision, technological innovation and rural development from an end-user perspective and the implications thereof for energy access measurement and intervention designs.*

iii *A novel design for a bottom-up rural electrification process.*

The remainder of this chapter is dedicated to illuminating these points and to discussing main policy insights.

7.5.2 Where are we, where do we want to go, and how do we get there?

In 1878, Thomas Edison demonstrated for the first time in history his incandescent light bulb with the words *"[w]e will make electricity so cheap that only the rich will burn candles"* [Edison, 1878]. Historians at that time reckon that the world population was around 1.3 billion people [McEvedy and Jones, 1978]. That number should ring a bell. For 137 years the total off-grid population has more or less plateaued with some volatility in the late 20th century [Alstone et al., 2015]. Only in the past decade have we started to outpace population growth by bringing more people 'on the grid'. It is beyond any doubt that a global clean energy revolution is urgently needed [Ki-moon, 2011]; in fact, many people may argue that it is already well underway. However, despite the general agreement in the development community that sustainable energy for all (SE4ALL) in terms of ensuring universal access to modern energy services must be achieved by 2030 [Ki-moon, 2011], there are still at least three issues that to date remain unclear. First, what does universal energy access actually mean? Second, how do we get there? And third, if we don't have an answer to one, how will we even know when we arrive?

On-grid versus off-grid, centralized versus decentralized electricity access: the problem of dualism seems to run through the perception of energy access based on multiple observations. A binary assessment of energy poverty, consisting of the relative share of the population with access to the grid and to modern cooking fuels, is far too limited to understand the multi-faceted nature of energy poverty. At times, as it was found, this perception even ends up being misleading (Chapter 5). To stay with the example of South Asia: In Bangladesh and India, a household that sources its electricity from a SHS is considered 'off-grid', Nepal and Sri Lanka, in turn, consider SHS also as a means of electrification [Palit and Chaurey, 2013]. Yet, we keep citing a single global number, also ignoring the fact that access to electricity by no means implies complete alleviation of suffering from energy poverty as shown in chapter 5. Further expanding the database and analysis of chapter 5, a composite index of energy access can be computed by taking the weighted average: (Pi x k), where Pi is the proportion of households in the kth tier. This index can be aggregated across villages, districts, provinces, countries and regions. It allows countries to set their own specific targets, which can then be tracked over time. At the same time, a dashboard approach can be adopted, with a separate in-depth analysis of individual energy poverty attributes or indicators. This flexibility allows for a hybrid approach reconciling the *"advantages of a single easy-to-understand and -interpret composite metric with the legitimate concerns related to aggregating information of various kinds"* [Bazilian et al., 2010, pg. 14]. Conversely, another implication of the proposed multi-tier framework is discussed by the international energy access community. In the case of some countries, previously believed not to have an energy access problem due to their high share of national grid electrification, they may turn out to have a major energy access problem based on a very poor tier performance of their on-grid households. This may not only lead to challenges for the buy-in of some of the SE4ALL member governments into the scheme but also to a possible justification for the support of centralized power plants in the spirit of energy access.

The dualistic view of centralized versus decentralized is equally problematic as it undermines the notion of a continuum of electricity services (introductory chapter and chapter 6). In the on-grid world of a 'tier 4 to 5 level', most likely nobody has ever consciously paid to charge her mobile phone (at airports, on planes, trains etc., it is even free). For people suffering from energy service deprivation this is very common phenomenon. In India, home of about 320 million energy poor, a mobile phone charge costs between Rs. 5-8 (USD 0.1 on average) depending on the region. In Bangladesh it is more or less the equivalent amount in Tk. Applying some simple math, this comes to a kWh price for this service of around USD 10.50. This has significant adverse impacts on development opportunities for this part of the population. Empirical data discussed in the introductory section shows that after having received basic energy access, energy use plateaus while human development continues to increase. Chapter 2 aimed to shed some light on the posed question of the causality between energy poverty and human development. Its main contribution lies in the development and empirical analysis of the energy poverty penalty concept (EPP). Further research is needed here, but based on the discussions it can be hypothesized that the EPP is at play as a specific form of poverty trap before this energy use plateau can be reached. Once it is reached, the ground is set for increased human development without significant increases in energy use up to a threshold where the relationship changes again. Pereira et al. [2011] set this threshold at 10 GJ/year of direct energy consumption per rural household based on empirical data from Brazil [Pereira et al., 2011]. This value ranges at the top of a tier 1 level, almost reaching tier 2 (threshold at 11.41 Gj/year or a 100kWh annually) as suggested by ESMAP in their proposed multi-tier consumption based energy access framework (Chapter 5). This value may at least give some insights on where we actually want to go when we talk about universal electrification.

Rural electrification based on solar PV has gained considerable prominence globally, as well as momentum in some regions. The success of these MES, however, has been fairly limited to date. Exceptions do exist. At the forefront unarguably is the case of Bangladesh with its 3.7 million SHS installed, and that only when counting the regulated market (Chapter 3 and 5). These successes have in fact led to an understanding that *"off-grid electrification becomes a viable complement to conventional electrification approaches"* [Khandker et al., 2014, pg. 1]. Other examples can be found in countries like India, Ethiopia, Kenya, Tanzania, and Peru [Jacobson, 2015]. Nevertheless, aggregated numbers on a binary scale hardly reflect these advances, first of all for the simple reason that SHS are often not considered as providing access to electricity, let alone mention of basic solar lanterns. A measurement over a graded scale (multi tiers) based on a range of attributes applied broadly in household censuses will shed much more light on the global situation of energy poverty. However, we are far from a consensus on the candidate proposal being put forward by the International Energy Agency and the World Bank. A range of suggestions on how to move towards such a consensus have been discussed in chapter 5. Secondly, one can rightfully say that progress for facilitating electricity access has in fact been very slow. If we agree for a moment that SHS provides some sort of electricity access, literature reveals at least three key elements for a major take-up of the same [Friebe et al., 2013; Khandker et al., 2014]:

1. Bringing down system cost;
2. Establishing a well-functioning after-sales service;
3. Having customer support in financing the assets in place (based on the availability of long term capital for the institutions themselves).

Asaduzzaman et al. [2013] compute price elasticities ranging from 8.6 to 41.4 for different sizes of SHS, implying that a 1% fall in price increases demand for the smallest system (20

Wp) by 8.6% and 41.6%, respectively, for a 65Wp SHS [Asaduzzaman et al., 2013]. Due to high competition, technological progress and decreasing panel cost prices have come down significantly in the past, and having led to major up-take of SHS, underlining element 1 in the list above. Prices for SHS in Bangladesh are relatively low compared to other areas in the world. At the same time, the market has turned from a supplier driven to a consumer driven market in a very short time of the past twelve months with the rise of the non-regulated market. Without well-functioning after-sales services, customer satisfaction will suffer and consequently so will sales. Without customer support in financing these new assets, usually the up-front cost is prohibitive for most of the customers. A pre-condition to point three is further the availability of long-term capital that in the case of Bangladesh is coming from the international donor community, provided to the implementing institutions. The whole package may be labeled a necessary eco-system for SHS adoption at a larger scale. If this eco-system is absent, a scale-up seems extremely difficult to achieve. In Bangladesh, the semi-governmental Infrastructure Development Company Ltd. (IDCOL) has received more than USD 500 million from multiple international donor organizations since the initiation of its SHS program in 2003, to build an industry, or an eco-system, around the SHS market [IDCOL, 2014]. As a result, by 2012 there were more than 40 partner organizations (PO) that had created employment for rural communities through the establishment of the program, incl. 3,000 direct and 5,000 indirect jobs, ISO standards, local SHS industry, almost 80 suppliers of solar PV, 13 battery manufacturers, etc. [Aziz and Chowdhury, 2012]. Long-term financing from the WB to IDCOL and then again to the POs is further guaranteed. This, in turn, allows the POs to apply a microcredit-based delivery mechanism, at 6-12% flat interest rate in combination with a 10-15% down payment of the system cost [Khandker et al., 2014]. Hünteler [2015] argues that local learning and industry building has a bigger impact on bringing down the cost for renewable energy than any international effort [Hünteler, 2015]. Further to that, what is produced locally is typically also more easily repaired locally, speaking in favor of a well-functioning after-sales service. After Bangladesh there is only one other country in the world that has had a considerable up-take of SHS compared to total population: Kenya [Jacobson and Kammen, 2007; Khan and Brown, 2015]. And Kenya, too, has a thriving solar-based industry [Ondraczek, 2013]. Again, causality cannot be proven and further there may as well be a catch-22 problem here but it remains an interesting observation worth to be looked into further. As utilities are unable to reach the majority of the energy poor through grid extension in a 2030 scenario [IEA, 2011], the private sector is called upon. But, the case made above clearly shows that in the absence of a suitable eco-system, which is the case in the large majority of the countries, a private sector approach is extremely difficult to realize. Intelligent deployment of donor money should therefore target the set-up of an energy service infrastructure leading to a suitable eco-system. This result is supported by findings in chapter 2. At the same time, different markets require different degrees of considerations for a functioning eco-system. Contrary to the results found in Bangladesh, the findings for the case of Peru suggest that income (affordability) is not the primary factor for an energy poverty penalty, in part indicated on the macro level as well by the strong divergence of Peru's HDI and EDI values. Remoteness as the physical distance to energy service infrastructures seems to play the bigger role here which in turn, however, has often been proven not economically viable to extend. Despite the successes in Bangladesh and Kenya, a large part of their rural populations remain excluded. Friebe et al. [2013] find that SHS are typically delivered successfully to households with incomes greater than USD 1,000 per year [Friebe et al., 2013]. That SHS target the sweet spot of the energy poor population can be confirmed for Kenya

[Lay et al., 2013] and Bangladesh, where average income of adopter households is at USD 2,000 on average 80% higher than the income of non-adopter households [Asaduzzaman et al., 2013]. Latest empirical data analyzed in chapter 5 confirmed these observations. The question remains how this translates into progress on energy poverty when measured by the multi-tier framework. The higher the benchmark level of energy poverty (presumably in case of a sweet spot), the lower the net progress (provided a certain energy intervention like a SHS comes with a maximum achievable tier level).

Independent of the measurement approach, latest statistics on collection efficiency show alarming signals for the major POs in the Bangladeshi SHS program, bringing the market as a whole into a very difficult position as a consequence of the rapid shift from a supplier to a consumer driven market. Stronger competition has led to increasing pressure on sales 'beyond the sweet spot' and less care for customer selection and retention. It is likely that the market has already passed a critical limit that was estimated to be at 4 to 5.12 million systems [Asaduzzaman et al., 2013]. It is, therefore, possible that a market adjustment is imminent which will bring about a retro-fit market potential. Triggered by these results and observations, chapter 3, 4, and 6 were dedicated to new designs of MES aiming to address some of these shortcomings and representing a new trend in rural electrification which is further elaborated upon in the last chapter of this thesis.

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Chapter 8

Outlook

"Decentralization and democratization of energy go hand in hand with a transition to a more equitable society."

- Ole Hendrickson,
2015

Outlook

8.1 New trends in rural electrification

In the past five years, in the absence of a favorable eco-system, a clear sector trend has been to focus on products that require the least number of enabling elements. Solar lanterns are least in need of market linkages, financing and after-sales infrastructure when compared with other MES, and their scale-up still required significant support from overarching bodies. The International Finance Cooperation (IFC) has set up a massive program, the Lighting Global Initiative (originally Lighting Africa), to support the sector mainly through quality assurance mechanisms [Jacobson, 2015]. D.light has set the standard in this sector with 10 million installations since beginning operations in 2008 and operating on a commercial model that reached the attention of private sector investors. They managed to raise USD 40 million in a mix of social and venture capital, whereas Africa based companies like M-KOPA Solar and Off-Grid Electric accumulated USD 43 million in financing [Hepler, 2015]. These are strong signals for scale-up. Against this backdrop, it seems paradoxical that this 'entry-level' technology provides modern lighting and phone charging, and is restricted to a tier 0 level as per the candidate multi-tier framework in its present form.[1]

In the same time frame, the ICT sector has set the example with its considerable success in marketing a leapfrog technology at the Base of the Pyramid (BoP) [WB, 2012; Nique and Smertnik, 2015]. The mobile phone carries an up-front investment and then recurring costs typically based on a pre-paid scheme. Many MES operate on a similar payment model, be it through microcredit or microleasing, both usually combined with a down payment, or through fee-for-service models with connection fees. Associated end-user costs of the two technologies for many types of MES differ, in the case of solar lanterns, however, they don't. The crucial element to success is often stated to be the consumer demand [Khandker et al., 2014]. Here, it is reasoned, limited affordability results in limited adoption of SHS [Friebe et al., 2013]. In that case microfinance could do the trick. However, despite the great potential of the combination between energy access and microfinance, Groh & Taylor [2015] come to the conclusion that the outreach of this synergy has remained very limited to date [Groh and Taylor, 2015]. Furthermore, demand is defined over affordability and willingness to pay, both need to be in place. Therefore, in the cases where cost is comparable, the associate value for certain MES must be lower than for a mobile phone, or else other factors need to be at play here. And this still does not address the claimed substitution effect in terms of avoided kerosene expenditure which has been shown nonexistent in the case of Bangladesh, at least not to a 1:1 degree or better [Chapter 5]. At the same time, this oft relied upon comparison between the mobile phone and energy access industry seems to fall short since the latter is organized highly decentralized whereas the mobile phone industry is a highly centralized and standardized.

Payment flexibility is often an underestimated factor of the affordability criterion [Moreno and Bareisaite, 2015]; [Chapter 6]. An excellent example for new trends in solar electrification for the scale-up of SHS, is the piggybacking of the PAYG models on the successful ICT infrastructure or eco-system, aiming to decrease payback risk, increase payment flexibility and

[1] Note: A last minute change in the definition of the capacity attribute of the multi-tier framework has been trying to fix this problem refer to footnote 6 also.

bring down operational last mile service cost (M-KOPA Solar, Off-Grid Electric, as mentioned earlier, or Mobisol are examples for this). In many developing countries, nowadays, the opportunity to top-up your mobile phone is available all over the country, as well as small repair shops for the same. The eco-system for the solar home systems in Bangladesh goes in the same direction, where efforts are made to de-skill the after sales process in order to allow for after-sales infrastructure in remote areas [Müller et al., 2009]. Among the hypotheses for chapter 6, as well being a topic for further research, is that the value proposition for an end-user of a mobile phone, in addition to mimicking the mobile payment flexibility, are crucial tools for successful implementation of MES. From a poverty reduction perspective, short-term poverty relief based on a substitution effect is limited as no new income is generated. As discussed by Sovacool et al. [2012], access to electricity and mechanical power for income generation activities should, therefore, be key areas of focus [Sovacool et al., 2012]. Chapter 3 discussed design principles for a special kind of MES, that *"has become scientifically, technically, politically, organizationally, and socially a true hot-bed of innovation"*: microgrids [Schnitzer et al., 2014, pg. viii], that so far could not live up to the promise on delivering a viable model to address these issues. Even though there is large variety of minigrid designs, ranging from the traditional model of centralized storage and generation to more recent versions where decentralized storage and generation are applied, as well as all possible combinations of the same [Chowdhury et al., 2015], a large body of literature and the great majority of installations follow the 'laid down AC-based system path' which is only slowly changing. Besides technological reasons for leapfrogging, market models that emerged with the mobile phone revolution like sharing phones in the future may serve as a precedent for smart grid schemes, such as swarm electrification [Welsch et al., 2013]. Against this backdrop, chapter 6 took the discussion on innovations a step further introducing the swarm electrification approach that investigates an evolutionary path from SHS deployment, over local micro-grids, to the national grid (or at least regional grids). It is a concept that again may open up new trends in rural electrification despite any doubts of its practical feasibility.

Where there is no doubt and therefore more importance in the run-up to the Paris climate negotiations 2015 is the assertion that a future push for rural electrification stands in no conflict to efforts to mitigate climate change [Pachauri, 2014]. The perspective to be taken in Paris should rather be on the findings that raising basic living standards contribute less to CO2 emissions than growing affluence [Rao et al., 2014]. This argument is further reinforced by recent results leading to the conclusion that supporting people to gain high levels of access to basic needs is attributed to lower emissions compared with continued economic growth [Lamb and Rao, 2015]. It is equally in line with the introductory remarks reflecting on research by Steinberger and Roberts [2010] that given saturation effects at high levels of energy consumption, and rebound effects in combination with increased efficiency of the delivery of essential energy services, high levels of human development for all is possible at current, if not lower, global energy consumption levels [Steinberger and Roberts, 2012]. Those need translation into clustered tier levels.

8.2 Future research

The overall contributions of this thesis aim to give a better understanding of the measurement and design of interventions targeting energy poverty in a developing country context.

Nonetheless, in the spirit of innovation, the thesis also brings up new problems and carves out new trends that could not be addressed satisfactorily within its scope. These should form the basis for future research questions that potentially can build on the presented results. Whereas the feasibility of the swarm electrification approach from chapter 6 remains to be proven in practice, the concept opens up new discussions on the extent that electricity services could be decentralized and democratized in a Global South setting. A similar model, yet for a different context, is outlined by Kolhe [2012] describing future smart grid power systems as networks that will manage *"bi-directional energy flows, linking widely distributed small capacity renewable energy systems at the consumer level (distribution network) [...], facilitating active participation of customer choice for energy production/source and demand management, and providing real-time information on the performance and optimum operation of the power system network"* [Kolhe, 2012, pg. 89]. The case study of chapter 6 goes in the same direction with the exception that it is based on dense clusters of distributed small capacity renewable energy systems (SHS) and that the cost-benefit analysis of additional smartness with regards to remote system management has to be based on different parameters. *"When you've had a monopoly for a hundred years, and you've never seen change, change may seem like death to you"* [Crooks, 2015]. The quote is by Lyndon Rive, the CEO of SolarCity [2], in response to the fear of US utilities that solar increasingly decentralizes the power supply which may threaten the utilities' market position. The situation for many utilities in the Global South is rather different being confronted with severe generation caps due to restricted capacity paired with limited interest in going into areas often characterized by insufficient load profiles and physical remoteness, among others. Their reluctant drive for innovation, when it comes to decentralized systems, often based on solar, however, seems to be very similar. The bold announcement by Elon Musk of a start into a decentralized USA [Clover, 2015], coupled with a strong push for R&D and roll-outs for smart grids and meters in the European Union (EU) [EC, 2015], triggered a lot of attention throughout the globe. At the same time, through grassroots innovations, a range of smart and just grids are currently popping up in the Global South, including local charging stations, digital finance, load prioritization and smart tariffing, among others. A couple of them have formed the case study basis of this thesis. These seemingly parallel trends in the Global North and South bear a great potential of future research, including possible reverse innovations [Govindarajan and Trimble, 2012].

A selection of future research questions is provided hereafter:

- What is the optimal level of energy measured at the useful level from an end-user perspective that facilities human development (given that they are dynamic and have turning points in the relationship) and how can those be translated into different tier levels to be achieved on average?
- What is the role of lock-ins under a concept of a continuum of electricity services?
- To what extent can gap analysis on the basis of the candidate framework to measuring energy access inform strategies to improve the eco-system for energy service delivery?
- What is the relationship between income and energy poverty against the backdrop of different energy interventions, different income distributions and respective tier ratings?

[2] For further information on the US solar company: `http://www.solarcity.com/`.

- How can the merits from smarter energy infrastructure be better reflected by the multi-tier framework?
- To what extent can energy service quality be further improved through innovative schemes targeting both payment and electricity service use flexibility?
- To what extent can the Global South benefit from developments in the field of smart grids and meters in the Global North (given that smartness always comes at a cost and limited capacity to pay at the end-user level in the Global South)?
- To what extent can the Global North benefit from developments in the field of smart grids and meters in the Global South through reverse innovation?
- What is the role of smart and just grids for SE4ALL?

More systemic research seems to be urgently needed in order to be able to monitor and pursue the universal electrification goal of the SE4ALL, and hopefully also the proposed SDGs 7 and 9.

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Chapter 9

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